TECHNICAL REPORT S-68-9

DESIGN AND EVALUATION OF A DEVICE FOR DETERMINING THE ONE-DIMENSIONAL COMPRESSION CHARACTERISTICS OF SOILS SUBJECTED TO IMPULSE-TYPE LOADS

by

L. Schindler

November 1968

Sponsored by

Defense Atomic Support Agency

Conducted by

U. S. Army Engineer Waterways Experiment Station
CORPS OF ENGINEERS
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ARMY-MRC VICKSBURG, MISS.

FOREWORD

This report was prepared in the Soils Division, U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Miss., under the sponsorship of the Defense Atomic Support Agency (DASA) as part of NWER Subtask RSS 2209, Propagation of Ground Shock Through Soils. The work was accomplished during the period January 1964 through August 1967. During this time, Mr. W. J. Turnbull was Chief of the Soils Division, and Mr. R. W. Cunny was Chief of the Soil Dynamics Branch.

This report, prepared by Mr. Larry Schindler, is essentially a thesis submitted to the University of Illinois, Urbana, Ill., in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Civil Engineering.

Directors of WES during the conduct of this study and the preparation of this report were COL Alex G. Sutton, Jr., CE, COL John R. Oswalt, Jr., CE, and COL Levi A. Brown, CE. Technical Director was Mr. J. B. Tiffany.

DESIGN AND EVALUATION OF A DEVICE FOR DETERMINING THE ONE-DIMENSIONAL COMPRESSION CHARACTERISTICS OF SOILS SUBJECTED TO IMPULSE-TYPE LOADS

BY

LARRY SCHINDLER

B.C.E., College of the City of New York, 1960
M.S., University of Illinois, 1961

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Civil Engineering
in the Graduate College of the
University of Illinois, 1968

Urbana, Illinois

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DESIGN AND EVALUATION OF A DEVICE FOR DETERMINING THE ONE-DIMENSIONAL COMPRESSION CHARACTERISTICS OF SOILS SUBJECTED TO IMPULSE-TYPE LOADS

Larry Schindler, Ph.D.
Department of Civil Engineering
University of Illinois, 1968

A general-purpose test facility for determining the one-dimensional compression characteristics of soils subjected to impulse-type loads has been developed in order to help satisfy the ever-increasing demand for reliable soil-property data required in support of a wide variety of nuclear-weapons-effects-related problems. The design, fabrication, installation, and evaluation of the various elements which together comprise the test facility were accomplished at the U. S. Army Engineer Waterways Experiment Station (WES), where much of the Defense Atomic Support Agency-sponsored, nuclear-weapons-effects research program is conducted.

The various considerations involved in the design and evaluation of the newly developed test facility are discussed in detail, thus providing some insight into the types of factors which affect the experimental-accuracy capability of a one-dimensional compression test facility and thereby the reliability of the data obtained under any particular set of conditions. It is shown herein that a test facility of the type developed at WES is characterized by great versatility and a high-quality-performance capability. Equipment of the type developed can be used to conduct tests for purposes of fundamental research as well as for practical engineering applications, on either prepared or sampled specimens of all soil types,

within a broad range of peak pressures and loading durations that is associated with nuclear-weapons-effects problems. The experimental-accuracy capability of the WES facility is estimated to be ±3 percent for carefully controlled tests and ±7 percent for routine tests.

The versatility and performance characteristics of the general-purpose, one-dimensional compression test facility developed at WES stem from the use of a new piston-fluid loading technique in conjunction with the multiple-reflection testing technique. Of the several techniques which have been or are being used to determine the one-dimensional compression characteristics of soils subjected to nuclear-weapons-induced loadings, the multiple-reflection testing technique is shown to be the only one which appears to be suitable for use in conjunction with general-purpose testing. The concept upon which the new loading technique is based is formulated when an examination of the several test facilities already employing the multiple-reflection testing technique reveals that they are subject to certain limitations which are directly related to the nature of the load-application system used in each case.

ACKNOWLEDGMENT

The work reported herein was conducted in the Soil Dynamics Test Facility of the U. S. Army Engineer Waterways Experiment Station (WES) as part of the overall nuclear-weapons-effects research program sponsored by the Defense Atomic Support Agency (DASA) at WES, through the Office of the Chief of Engineers (OCE), Department of the Army. The support of all three organizations--WES, OCE, and DASA--is gratefully acknowledged. The author considers it a privilege to have been associated with the Corps of Engineers and WES in general and with the Impulse Loads Section at WES in particular.

The number of people who have contributed in some way to the successful completion of this dissertation is so large that individual recognition would be impractical. The author is indebted to his colleagues in the Impulse Loads Section of the Soil Dynamics Branch at WES for their ideas, comments, and criticisms throughout the conduct of the work and the preparation of the dissertation; to the laboratory and instrumentation technicians for their assistance in the laboratory phase of the work and in the reduction of the data obtained; to the staff of the WES shops, particularly the machine shop, for fabricating the device described herein and its numerous appurtenances; to the staff of the Reproduction and Reports Branch at WES for their extensive assistance in the preparation of the manuscript; and to the staff members of the various other elements at WES, such as the Purchasing Branch and the Technical Library, for their support. The author is also indebted to a number of the members of the faculty at the University of Illinois, particularly those on his thesis committee, for their advice

and constructive criticism, and to the various other investigators in the nuclear-weapons-effects-research community who permitted him to visit their facilities and inspect their one-dimensional compression equipment. The assistance and liaison service provided by Mr. P. L. Marsicano of WES during the period following the author's transfer from WES to OCE (and before the preparation of the manuscript was completed) is appreciated.

The author is particularly grateful to his supervisor at WES, Mr. J. G. Jackson, Jr., Chief of the Impulse Loads Section of the Soil Dynamics Branch, to his present supervisor at the Office of the Chief of Engineers, Mr. N. G. Hansen, Chief of the Missiles and Protective Structures Branch of the Directorate of Military Construction, and to his adviser, Dr. R. B. Peck, Professor of Civil Engineering, for their advice, assistance, and personal interest, and--above all--for their patience.

Special gratitude is due Mr. G. C. Downing of the Instrumentation Branch at WES for his advice and assistance in the design and evaluation of the instrumentation system for the one-dimensional compression test facility described herein and for his comments, suggestions, and assistance in connection with the preparation of the dissertation. Special gratitude is also due Dr. H. O. Ireland, Professor of Civil Engineering, for his help at a very crucial time; Dr. Ireland's assistance in identifying the interface mismatch as the root of the equipment-compressibility problem is gratefully acknowledged.

The author extends his sincere and deep appreciation to his wife for her patience and understanding and for the encouragement which she provided during the several years which were required for the completion of the work and the preparation of the manuscript for this dissertation. In addition,

her direct assistance at several crucial times, both as laboratory technician and editor, is gratefully acknowledged.

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CHAPTER 1

INTRODUCTION

1.1 Background

The response of a buried protective structure to the combined effects of air blast and ground shock from a nuclear explosion is highly dependent on the constitutive properties of the soil (or rock) in which the structure is buried.

As the ground shock propagates through the soil from the explosion to the structure, its energy is attenuated in part in accordance with the constitutive equations of state or stress-strain-time characteristics of the material through which it propagates. (Its energy is also attenuated in part, as is that of the air blast, as a consequence of geometry.) The more energy which the soil can absorb, the lower the levels of stress and ground motions which reach the vicinity of the structure. Thus, the constitutive properties of the soil "upstream" from the structure affect the input to the structure and to the soil mass in its immediate vicinity.

When the wave fronts of the air blast and the ground shock disturbances reach the vicinity of the structure, their dimensions are generally large relative to those of the structure. The result is the nearly simultaneous loading of a large mass of soil around the structure. The ground motions experienced by this mass--and consequently the gross motions experienced by the structure suspended in it--depend primarily on the constitutive characteristics of the material in the mass and the material "downstream" from it. Furthermore, as load from both the air blast and ground shock propagates through the structure and the various structural

elements deform in accordance with their response characteristics, the soil in the immediate vicinity of the structure helps to limit these structural deformations as well. Thus, the constitutive properties of the soil at the structure and "downstream" from it affect the gross motions experienced by the structure as a whole and the deformations experienced by the various structural components.

Because the response of a protective structure is so sensitive to the constitutive properties of the soil in which it is buried, it is important--for the siting, design, and analysis of each installation--to be able to determine these properties accurately. Conventional test equipment is not well suited to this purpose, since it is unlikely that properties obtained in this manner will accurately reflect the behavior of the material when it is subjected to short-duration, high-amplitude, impulse-type loads characteristic of the air blast and ground shock from a nuclear explosion. Consequently, it is desirable to design special test equipment and related instrumentation systems specifically for nuclear-weapons-effects applications.

The soil-property test which has received the most attention in nuclear-weapons-effects work is the one-dimensional compression test (also referred to as a uniaxial strain test, a constrained compression test, a confined compression test, or an oedometer test), a test in which no strain is permitted in the specimen normal to the direction of applied loading. The one-dimensional compression test has been used extensively to determine the compression characteristics of soils for conventional construction applications, and it has been found to be a very useful and convenient test. The geometry of the test is particularly well suited to protective construction applications because it represents a fairly good approximation of

the actual in situ conditions which exist in the vicinity of a nuclear explosion.

1.2 Statement of Problem

There has been during the past several years an ever-increasing demand for reliable data concerning the constitutive characteristics of various types of soils when subjected to impulse-type loads. Furthermore, there is every indication that the trend will continue in the future.

Test data under specific material and loading conditions are required in support of such diverse nuclear-weapons-effects-related activities as laboratory wave-propagation studies of free-field response, laboratory similitude studies, laboratory and field studies dealing with the evaluation of various types of instruments and techniques for placing them into a soil mass, large-scale high-explosive and nuclear field tests for various research applications, field evaluation of existing installations, and selection of sites for future installations. General behavioral characteristics of soils of various types are required to support the development of reliable analytical free-field codes which represent actual soil behavior.

There is also a need for fundamental studies of various types. The influence of such parameters as stress history, moisture content, loading and unloading rate, lateral confinement, compaction effort, and sample disturbance on the constitutive characteristics of various types of soils is still not well understood. The possibility of relating constitutive properties of soils to simple, more-easily-obtained index properties has not been adequately explored.

The problem is apparent. There has been, and there continues to be, a need for the development of laboratory equipment of all types for determining soil properties for nuclear-weapons-effects applications. Particularly acute, because of the broad-based nature of the demand for data, is the need for multipurpose (or general-purpose) equipment, equipment which can be used to conduct tests for purposes of fundamental research as well as for practical engineering applications--on either prepared or sampled specimens of all types--within some fairly broad range of peak pressures and loading durations that is associated with nuclear-weapons-effects problems (Glasstone, 1962; Newmark and Haltiwanger, 1962; Sauer, Clark, and Anderson, 1964).

1.3 Scope of Report

The need expressed above for the development of general-purpose laboratory equipment is for several types of devices, each specifically designed to isolate and examine a particular feature of the overall constitutive relationship that is indicative of material response under general loading and boundary conditions. The investigation reported herein was concerned with one such device, the one which isolates the most important feature of the overall constitutive relationship of a material for nuclear-weapons-effects applications, the one-dimensional compression device.

The immediate objectives of the investigation were (1) to develop a general-purpose one-dimensional compression device, with all the associated appurtenances, for use in support of the various nuclear-weapons-effects-related problems outlined above, and (2) to provide sufficient insight into the types of factors which affect the experimental-accuracy capability of

the test facility as a whole to permit evaluation of the reliability of the data obtained for any particular set of conditions. It was hoped that the results of the investigation would materially contribute (1) to establishing the feasibility of using a single general-purpose device to determine the one-dimensional compression characteristics of soils subjected to nuclear-weapons-induced loadings for a broad range of material, loading, and application conditions, and (2) to developing a set of design criteria and concepts for a model, general-purpose, one-dimensional compression test facility for nuclear-weapons-effects-related problems.

The work undertaken to meet the stated objectives was accomplished in three stages, each of which is reported separately herein. The following chapter, Chapter 2, deals with the conceptual aspects of the overall design of the test facility. All available information concerning the one-dimensional compression testing of soils for nuclear-weapons-effects applications is reviewed. Of all the different testing techniques considered, one is found to be particularly well suited to general-purpose applications. When the several test facilities employing this particular type of testing technique are found to be subject to certain limitations which are directly related to the nature of the load-application system used in each case, a new technique for load application is proposed for the general-purpose test facility to be developed.

The specific design details for the general-purpose test facility actually developed are described in Chapter 3. Both original design considerations and modifications subsequently found to be required are presented therein. Particular attention is devoted to the several innovations incorporated, including the new technique for load application, and

the impact of these innovations on the performance and versatility characteristics of the test facility as a whole.

Chapter 4 deals with the comprehensive experimental program undertaken to evaluate the device that was developed and its various appurtenances. The significant aspects of the evaluation program and the results obtained are described in detail in order to provide an insight into the various types of factors which affect the experimental-accuracy capability of the test facility developed and that of one-dimensional compression test facilities in general. The facility is shown to be characterized by greater versatility and better performance than is possible with other equipment of this type. Facility limitations in connection with general-purpose applications are summarized, and methods are considered by which each limitation can be eliminated or its significance diminished.

The most significant results of the investigation are summarized in Chapter 5, as are the conclusions reached on the basis of the results. Also included in Chapter 5 are some recommendations for future work.

1.4 Definitions and Usage

One of the principal difficulties inevitably associated with complex programs which draw upon the talents of investigators with widely differing technological backgrounds is the confusion which results from the differences in terminology and symbology associated with different fields of endeavor. An attempt has been made herein to avoid the use of terminology and symbology which may mean different things to different individuals. Wherever there may be some question concerning the intended meaning of an expression or the use of a symbol, a definition or explanation is

provided. Expressions and terms not in general use are defined where they first appear.

British units of measurement are used throughout this report. Factors for converting these units to metric units are provided in Fig. 1.

Multiply	By	To Obtain
microinches (μin.)	25.4	millimicrons
mils	25.4	microns
inches (in.)	2.54	centimeters
feet (ft)	0.305	meters
square inches (sq in.)	6.45	square centimeters
cubic inches	16.39	cubic centimeters
cubic feet	0.0283	cubic meters
pounds, avoirdupois (lb)	0.454	kilograms
slugs	14.6	kilograms
pounds (lb)	4.45	newtons
kips	454	kilograms
Fahrenheit degrees	0.556	centigrade degrees
gravity acceleration units (g)	9.81	meters per second per second
horsepower (hp)	0.746	kilowatts

Fig. 1. Conversion factors, British to metric units of measurement.

CHAPTER 2

CONCEPT CONSIDERATIONS

2.1 Introduction

2.1.1 General

The first stage of the investigation reported herein dealt with the application of available information to the problem at hand. Information concerning the fundamentals of soil behavior, the nature of soil properties, and the philosophy of soil-property testing was reviewed to provide a sound and rational basis for the decisions which would have to be made in connection with the design and evaluation of the general-purpose, one-dimensional compression test facility. After the review of the basic soil mechanics literature had been completed, a review of all the available information concerning the one-dimensional compression testing of soils for nuclear-weapons-effects applications was undertaken. The most significant results which emerged and the conclusions reached on the basis of these results are outlined in the sections which follow.

It is desirable at this time to consider some fundamental concepts which provide an introductory framework for the discussions which follow. The concepts considered fall into two categories, and they are presented accordingly. The first portion of the discussion deals with some fundamental concepts in the area of soil mechanics which pertain to the problem at hand. The second portion of the discussion deals with the key features of the one-dimensional compression test facility in general.

2.1.2 Soil Properties

It is beyond the scope of this report to examine the overall impact of fundamental concepts in theoretical and applied soil mechanics on the direction of the work conducted. A general understanding of fundamentals in soil mechanics can be readily obtained by referring to any of the standard textbooks on the subject (e.g., Jumikis, 1962, Scott, 1963, Sowers and Sowers, 1961, Taylor, 1948, Terzaghi and Peck, 1948, Tschebotarioff, 1951); within the nuclear-weapons-effects literature, the most comprehensive treatment of the subject appears in "Nuclear Geoplosics" (Whitman and Clark, 1964). The discussion presented below serves merely to gather in one place the various pieces of information dealing with fundamental concepts in soil mechanics that are required to support statements made elsewhere in this report.

General. The natural earth materials which comprise the earth's crust are porous in nature and are characterized by a structural skeleton consisting of mineral grains. The stability of the structural skeleton depends in part on the cohesive forces at the intergranular contacts, which may derive either from external sources such as cohesive foreign materials (binder) or surface tension in the pore water or from internal sources such as surface chemical forces; it also depends in part on friction at the contacts and on interlocking of the grains. Natural earth materials with high cohesive bond strengths at the intergranular contacts, strengths which approach those of the grains themselves, are collectively referred to as rock; those with lower bond strengths are collectively referred to as soil.

The response of a mass of soil (or portion thereof) to a given applied load depends on the physical characteristics of the mass, the characteristics of the applied load, and the boundary conditions. An indication of the contribution of the physical characteristics of the mass--the type of structural skeleton and the strength of the cohesive bonds at the intergranular contacts, the size and shape of the grains which comprise the skeleton and their distribution, the mineralogical composition of the grains, the degree of saturation of the pores or voids, etc.--can be obtained from the various examples depicted schematically in Fig. 2.

It should be apparent from the few examples shown in Fig. 2 that the characteristics of a soil mass at one location may bear little resemblance to the characteristics of a soil mass at another location. The differences ultimately stem from several sources--differences in the origin of the grains which form the skeleton of the mass, differences in the manner and/or vehicle of transportation between the point of origin and the point of deposition (e.g., water, ice, wind, gravity, man, and combinations thereof), differences in the environment during deposition, and differences in geologic history between the time of deposition and the time of interest. Consequently, even different portions of the same mass may be expected to have different characteristics; indeed this has been found to be the case.

Qualitative Response Characteristics. It appears from the various sketches of soil structure shown in Fig. 2 that the one-dimensional compression behavior of most soil masses under nuclear-weapons-induced loadings will be a complicated function of the physical characteristics of the mass. The stiffness of most materials will clearly be a function of

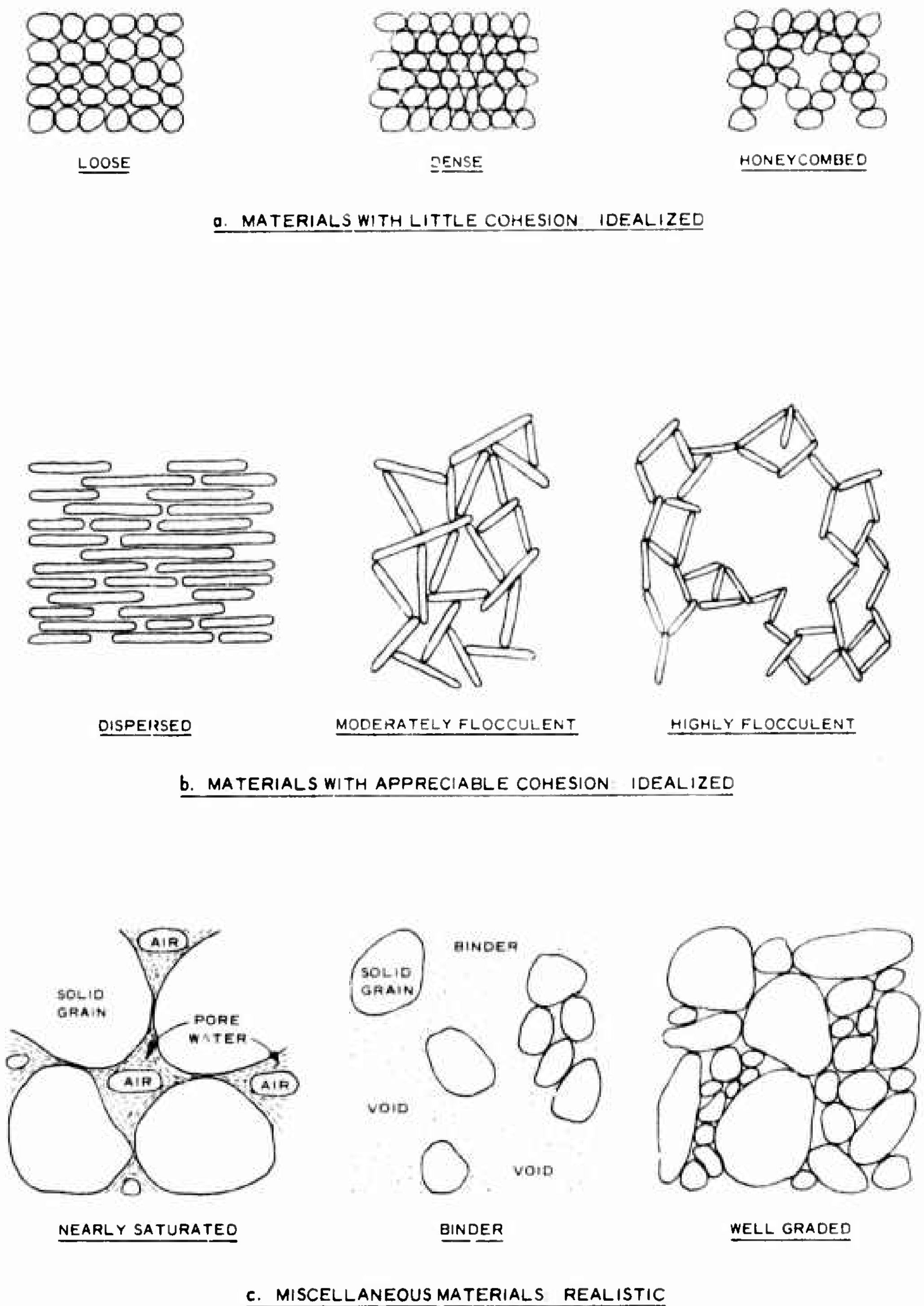


Fig. 2. Schematic sketches of soil structure.

the applied stress level, principally because the density--and, hence, the resistance to further compression--will increase with the level of applied stress. Another factor which contributes to the nonlinearity and the inelasticity of the response is the change in predominating response mechanism with stress level, during both loading and unloading. Applied stresses that are very small in amplitude are resisted primarily by the cohesive bonding forces and the friction forces at the intergranular contacts, with little or no actual densification taking place. As the level of applied stress is increased, the resistance at the intergranular contact points is eventually overcome, and the principal resistance mechanism becomes densification. For some materials, densification is soon replaced by grain crushing, which is then in turn replaced by further densification as the principal resistance mechanism to increased loads. At sufficiently high stress levels, the pore volume of nearly all soils becomes completely saturated, and the predominating response mechanism becomes the compression of the grains themselves and that of the pore water. Unloading response is clearly different from loading response since densification is essentially nonreversible. Furthermore, the cohesive bonding forces and the friction forces at the intergranular contacts are nondirectional, and they tend to resist unloading as well as loading. Consequently, to assume that the one-dimensional compression response of soils is either linear or elastic is a poor approximation of reality in most cases.

Although one can state with a fair degree of confidence that the response of most soils loaded in one-dimensional compression will be neither linear nor elastic, the matter of time dependency is not nearly so clear. Potential mechanisms for time dependency are abundant, as one

can see from examining Fig. 2. Grains can be arranged differently during densification; pore fluids under pressure can flow and transfer additional load to the structural skeleton; interaction amongst the three phases which comprise the soil mass can take several forms; the amount of pore air which can be dissolved in the pore water is time sensitive; etc. However, one can conclude from the information given above only that, qualitatively, soil response is in general time dependent. Still in doubt is the quantitative significance of time dependency under any given conditions. Until sufficient research has been conducted to resolve the doubt, it would be wise to assume that time dependency is significant in all cases.

Although the physical characteristics of soil masses can vary over wide limits, one particular condition, that of the fully saturated soil, is of special interest. When the pores or voids in a portion of a soil mass are completely filled with water, as is generally--but not always--the case below the water table, the response of the mass under one-dimensional-compression conditions is extremely rigid. The predominating mechanism of response under fully saturated conditions is compression of the pore water and the mineral grains; consequently, the stiffness of the mass exceeds the bulk modulus of water. Since the compression modulus of a soil mass undergoing densification is likely to be one or two orders of magnitude less than the bulk modulus of water, one should expect the response of a nearly saturated soil mass to be rather sensitive to small changes in both water content and stress level.

It is apparent from the discussion above and from Fig. 2 that the stiffness of a mass of soil is highly sensitive to the physical characteristics of the mass. Loose, dry, cohesionless materials and highly

flocculated cohesive materials will tend to be highly compressible under load. On the other hand, cohesive materials with high intergranular bond strengths and dense and/or saturated materials of all types will tend to be highly incompressible.

2.1.3 The Test Facility

The one-dimensional compression test has been defined above as a test in which no strain is permitted in the specimen normal to the direction of applied loading. Although many different types of laboratory test facilities have been and are being used to conduct this type of test, all can be characterized by the same four principal components--a specimen-containment system, a load-application system, a load-support system, and a measurement system. The specimen-containment, load-application, and load-support systems comprise what is generally referred to as the device or the test equipment. The primary function of the specimen-containment system is to provide the test specimen with a lateral boundary which is capable of maintaining the no-lateral-strain condition that characterizes the test. The load-application system includes those elements of the test facility which generate the short-duration loadings characteristic of the air blast and the ground shock from a nuclear explosion as well as the elements of the transition configuration required to transmit the load to the specimen. The load-support system provides the necessary reaction to the applied load.

The measurement system includes all the instrumentation, recording equipment, and associated appurtenances necessary to detect and provide a record of the various stress and motion histories which are

required to determine the response characteristics of the specimen and the test conditions under which they were obtained. The two key measurements in the system are those from which the stress and strain in the direction of the applied loading are determined. (The direction of applied loading is nearly always vertical; so, for convenience in presentation, the terms vertical stress and vertical strain are used hereinafter.)

2.2 Testing Techniques

2.2.1 Introduction

A preliminary review of the nuclear-weapons-effects literature available at the time this investigation was initiated showed that a number of organizations had already developed a laboratory capability for determining the one-dimensional compression characteristics of soils for nuclear-weapons-effects applications. In some cases, the equipment used was developed specifically for the property test; in other cases, equipment originally designed to be used for small-scale, one-dimensional, wave-propagation tests had been modified for use as devices for property testing. The organizations involved included Columbia University (Burmister and Stoll, 1963), University of Illinois (Hendron, Fulton, and Mohraz, 1963; Hendron and Davisson, 1963), Massachusetts Institute of Technology (Whitman, et al. 1959; Whitman, Roberts, and Mao, 1960; Healey, 1960; Moore, 1961; Whitman, 1963; Moore, 1963), Stanford Research Institute (Seaman, Bycroft, and Kriebel, 1963), and United Research Services, Inc. (now URS Corporation; Zaccor and Wallace, 1963).

The various types of testing techniques which were being used were carefully evaluated to determine their relative and absolute

suitability for use in the general-purpose, one-dimensional compression test facility which would be developed. The criteria used in the evaluation were based largely on the requirements associated with a general-purpose test facility. Restrictions on the amplitude or time characteristics of the applied loading pulse within the range of values associated with nuclear-weapons-effects problems were considered to be undesirable; restrictions on the type of material tested--sand, clay, silt, silty clay, etc.--or on the nature of the specimen--prepared in the laboratory or sampled from a soil mass--were considered to be undesirable; and restrictions on the experimental-accuracy capability of the facility were considered to be undesirable, since data would be obtained for research applications as well as for practical applications.

Restrictions associated with the applied load pulse and those associated with the specimen need not be considered at this time, since these can easily be recognized. It is desirable, however, to comment briefly on the types of facility characteristics which were thought to represent undesirable restrictions on the experimental accuracy which could be achieved.

Any type of experimental error introduced by the equipment itself, by the measurement system, or by any of the necessary appurtenances is of course undesirable. Experimental limitations are, however, inevitable, and some must be accepted. The criteria used herein to distinguish between acceptable limitations and those which were unacceptable were (1) severity and (2) compensability. Severe limitations were in general rejected; limitations resulting in small errors were generally considered acceptable. Errors which could not readily be evaluated were in general

considered to be unacceptable; errors which could readily be evaluated, so that the data obtained could be corrected, were generally considered acceptable.

The results of the evaluation and the conclusions reached on the basis of the results are discussed briefly below. It should be noted that equipment and concepts developed by others during the course of this investigation have been incorporated in these discussions. The organizations involved in the recent developments include the IIT Research Institute (Hampton and Wetzel, 1966), University of Illinois (Davisson, Maynard, and Koike, 1965), The Eric H. Wang Civil Engineering Research Facility of the University of New Mexico (Calhoun and Kraft, 1966), Stanford Research Institute (Seaman and Whitman, 1964; Seaman, 1966), United Research Services, Inc. (Zaccor, Mason, and Walter, 1964; Durbin, 1965), and U. S. Army Engineer Waterways Experiment Station (Ainsworth and Sullivan, 1967).

It should also be noted that only laboratory testing techniques are considered herein. Although properties of soil masses are occasionally determined in situ for certain conventional applications (in order to avoid the inevitable problems associated with sampling and sampling disturbance), laboratory testing is nearly always preferable to field testing when determining soil properties for nuclear-weapons-effects applications. The advantages of laboratory testing for determining the one-dimensional compression characteristics of soils for research-type, nuclear-weapons-effects applications are apparent. The reasons for the rejection of field-testing techniques for practical-type applications are considered in detail elsewhere, and need not be repeated herein (Zelasko, 1968).

It is important to recognize that there is no generally accepted

terminology for referring to the various types of testing techniques used to determine the one-dimensional compression characteristics of soils. The terminology used herein was selected specifically for this report and was introduced primarily for convenience in reference.

2.2.2 The Wave-Propagation Technique

The testing technique considered to be most appropriate, in principle, for the general-purpose, one-dimensional compression test facility is one, herein referred to as the wave-propagation technique, which affords the opportunity of simulating the various conditions of interest (see Fig. 3). The soil specimen is placed inside a rigid container, so that lateral strains in the specimen are restricted during the test. The desired loading is then applied uniformly to the surface of the specimen, and the parameters of interest are measured at the desired locations. (The two techniques shown in Fig. 3 for measuring the vertical stress and strain in the specimen are intended as examples only--other techniques can be used; velocity can be measured instead of strain, etc.)

Although the wave-propagation technique is most appropriate in principle, there are two very important problems associated with its implementation. Each of these problems provides sufficient grounds for rejection of the technique.

Specimen Size. One problem is the size of the specimen required. In order to afford the opportunity of measuring the vertical stress and strain at some location in the specimen while the applied load pulse propagates past that location, the test facility would require an extremely long specimen for most conditions of interest. The specimen should ideally be sufficiently long to permit the entire incident pulse

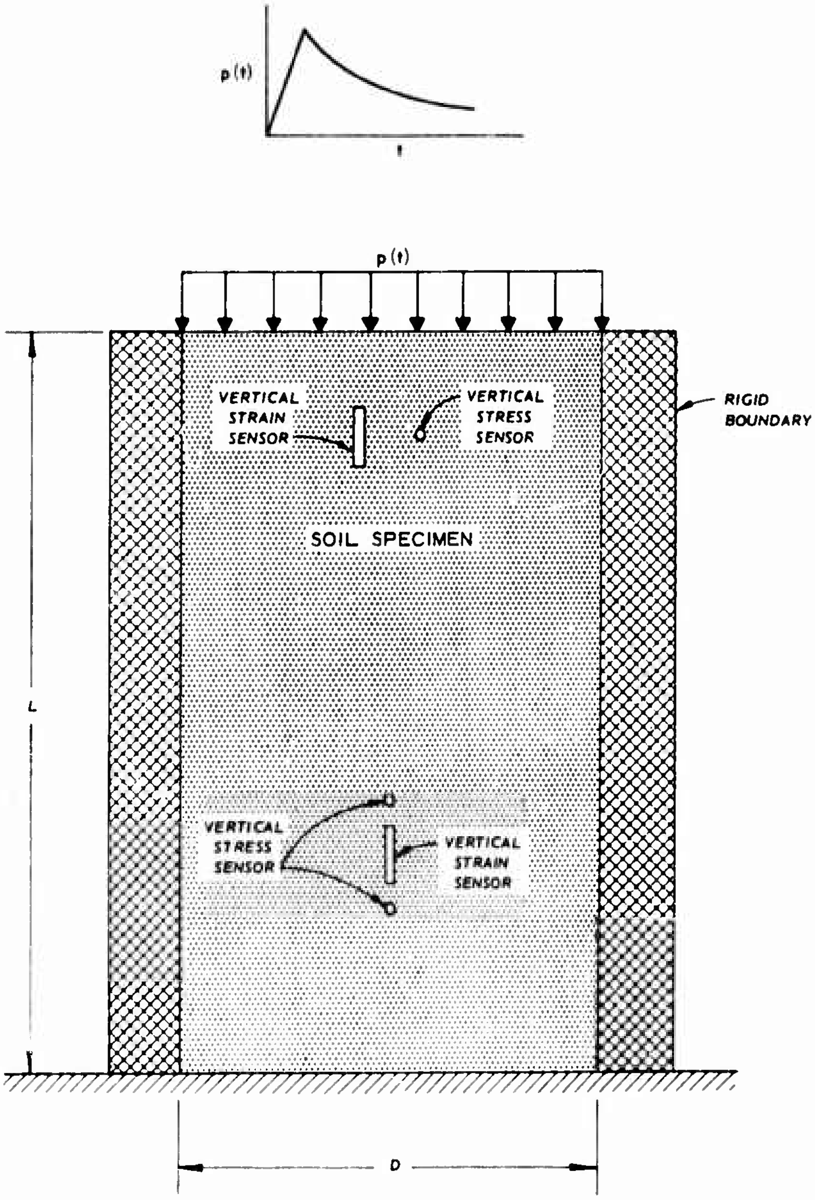


Fig. 3. Sketch depicting characteristics of wave-propagation testing technique.

to propagate past the instrumented portion of the specimen before the leading end of the applied pulse returns to this portion of the specimen after being reflected at the lower boundary of the specimen; for most conditions of interest, several tens of feet would probably be required.

The size problem is pertinent to the specimen diameter as well as to its length. When the specimen-containment system consists of a solid-ring boundary, such as the one depicted in Fig. 3, a specimen diameter several times larger than its length is required to minimize errors associated with sidewall-friction effects (see Section A.2).

Attempts have been made to eliminate the specimen-diameter size problem by using various friction-reducing techniques at the peripheral specimen boundary. Friction-reducing boundaries most frequently used include segmented rings, with and without intervening rubber spacers (Seaman, Bycroft, and Kriebel, 1963, and Zaccor, Mason, and Walter, 1964, respectively), greased membranes of various types (Abbott, 1965; Hadala, 1967) and membrane-contained fluids (Zaccor, Mason, and Walter, 1964). Although boundaries of these types have enjoyed some degree of success in reducing the amount of friction between the specimen and its peripheral boundary, they are subject to a few important limitations. They cannot be used conveniently in connection with good-quality sampled specimens, and are therefore not well suited to general-purpose equipment. Furthermore, the implementation of a friction-reducing technique inevitably introduces a certain amount of lateral flexibility into the soil-containment system. Therefore, until sufficient research has been conducted to determine the effect of lateral strain on the one-dimensional compression characteristics

of various soil types, it is probably advisable to avoid the use of friction-reducing boundaries.

It appears, therefore, that extremely large specimens would be needed for successful implementation of the wave-propagation testing technique. Since specimens of the size required are clearly impractical and economically unjustifiable, particularly in connection with a general-purpose test facility, the wave-propagation technique must be rejected.

Soil Gages. The other important problem associated with the use of the wave-propagation testing technique is the need for buried instrumentation. There is, of course, no method by which a gage can be placed inside a specimen, particularly a sampled specimen, without causing some disturbance to the specimen. The effect of the disturbance on the measurement obtained depends on a number of factors, including the placement technique, the type of gage, the quantity measured, the type of soil, and the type of specimen. In some cases, the effect probably is not important. A relative-displacement (or strain) gage specifically designed for use in soil specimens, for example, will probably provide an accurate indication of soil strain when used in a laboratory-prepared specimen. In general, however, the effect of the disturbance caused by gage placement is probably significant. Furthermore, the magnitude of the effect on the measurement obtained is in most cases difficult, if not impossible, to determine. Since the disturbance occurs in precisely that portion of the specimen where the measurement is made, confidence in the data obtained must necessarily be somewhat limited.

Specimen disturbance due to gage placement is not the only difficulty resulting from the use of buried gages. Another difficulty is the

effect of the presence of the gage on the response of the soil. The gage is, of course, a foreign inclusion in the soil specimen, and there is no reason to assume à priori that the response of the soil with the gage is the same as the response of the soil alone. In fact, since the gage measures response in precisely that portion of the specimen where the effect of the presence of the gage is probably the greatest, there is good reason to assume that the effect will be significant.

Some investigators have attempted to compensate for the presence of the foreign inclusion by calibrating the gage (that is, the inclusion) in place, under the conditions of the test. Unfortunately, the calibration test changes the properties of the specimen, so the calibration may not be appropriate for the property test which follows; furthermore, the initial conditions are known only for the calibration test, and not for the property test. Consequently, there is little to be gained from an in-place calibration of buried gages.

The use of buried gages to measure soil response clearly creates a number of important difficulties. Fortunately, alternative measuring techniques exist for other types of testing techniques, and these are described below.

2.2.3 The Multiple-Reflection Technique

Of all the different testing techniques which have been or are being used to determine the one-dimensional compression characteristics of soils subjected to nuclear-weapons-induced loadings, only one appears to be suitable for general-purpose applications. It is logical to consider that particular technique, herein referred to as the multiple-reflection

technique, at this time, since the two major problems shown above to be characteristic of the wave-propagation technique are both eliminated with the multiple-reflection technique (Fig. 4).

The fundamental difference in concept between the wave-propagation technique and the multiple-reflection technique, which permits the use of a short (or thin) specimen and indirect measurements in one case while requiring the use of a long specimen and direct measurements in the other, is that the former is a dynamic testing technique whereas the latter is basically a static-type testing technique. The key feature of the wave-propagation technique, as described above, is that it affords the opportunity of simulating all the conditions of interest by maintaining the transient conditions at each measurement location until the complete load-unload response is measured; hence, the complete history--strain, velocity, and acceleration--can be measured directly. The key feature of the multiple-reflection technique, on the other hand, is that it affords no opportunity for the development of significant inertial stresses within the specimen as the load-unload response is measured. It is important to recognize that, although velocities and accelerations are distorted in the static-type testing technique, the strain response to an applied load pulse of given characteristics is no different from the strain response to the same load pulse applied in a dynamic test, even for time-sensitive materials.

The method used to prevent the development of significant inertial stresses within the specimen is to place the rigid boundary at the bottom of the specimen in close proximity to the upper specimen boundary where the load is applied (Fig. 4). The time required for propagation

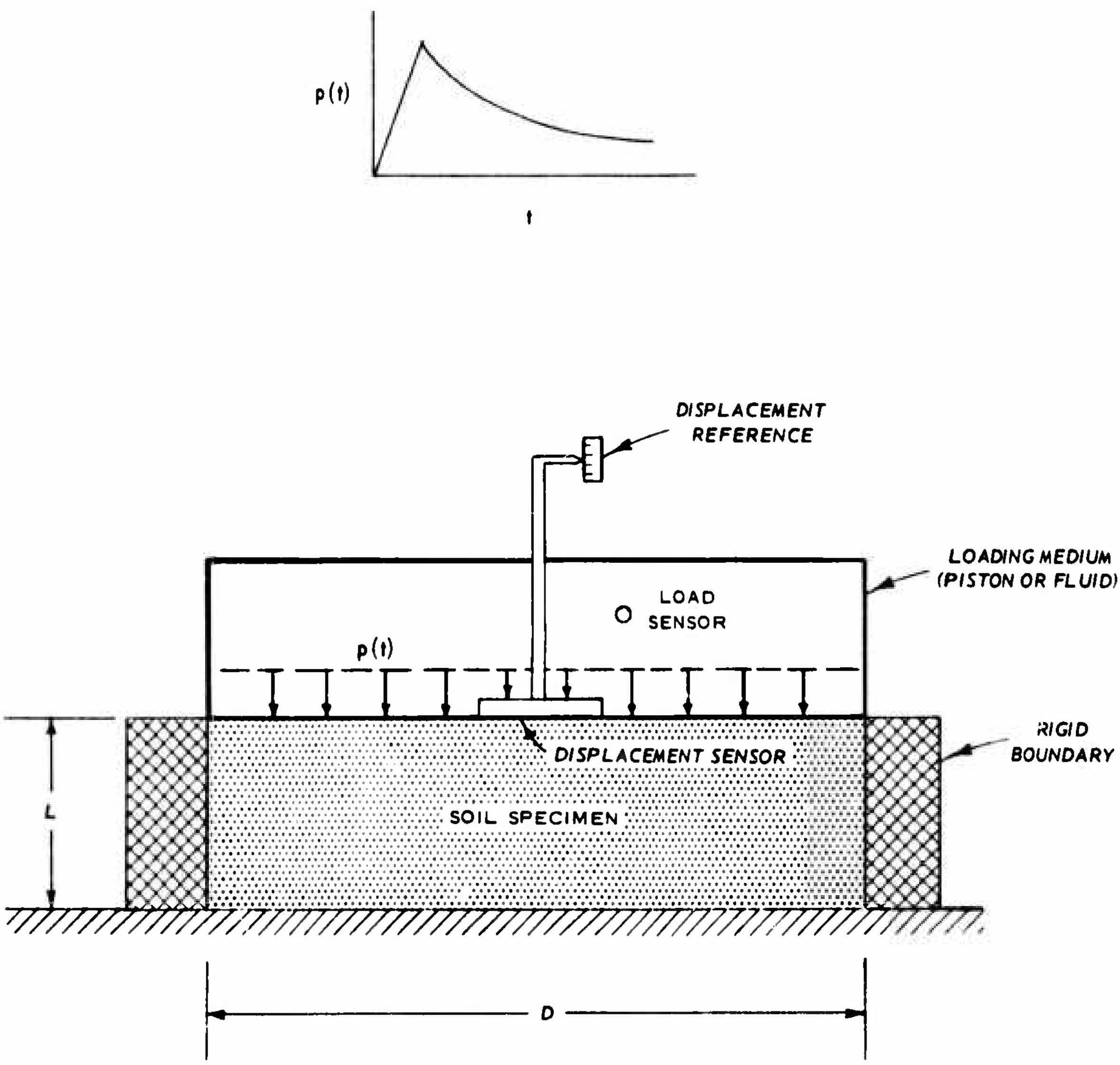


Fig. 4. Sketch depicting characteristics of multiple-reflection testing technique.

through the specimen is then so small relative to the rise time of the applied load that there is little or no opportunity for the development of vertical-stress differences; any which do occur are quite small relative to the peak stress value and are very soon eliminated as a result of internal reflections. Some indication of the conditions within a specimen during a test implementing the multiple-reflection technique can be obtained from the simplified example shown in Fig. 5; additional information can be obtained from a discussion prepared by Whitman (1963), the investigator who first used the multiple-reflection testing technique to determine the behavior of soils subjected to nuclear-weapon-induced loadings (Whitman et al., 1959).

The fact that the multiple-reflection technique eliminates the two major problems shown to be characteristic of the wave-propagation technique has already been mentioned. The use of a short specimen stems from the very concept upon which the technique is based. Direct measurements are not required by the multiple-reflection testing technique, since the average behavior of the specimen as a whole is what is determined and not the behavior of some particular portion of the specimen. As shown in Fig. 4, the vertical strain is determined by measuring the displacement of the specimen surface, and the vertical stress is determined by measuring the load transmitted to the specimen (pressure, in the case of a fluid; or force, in the case of a piston).

None of the problems found to be characteristic of the multiple-reflection testing technique were considered to be insurmountable. Of the few problems which could be identified in the early stages of the investigation, all but two pertain to details of the load-application system. These

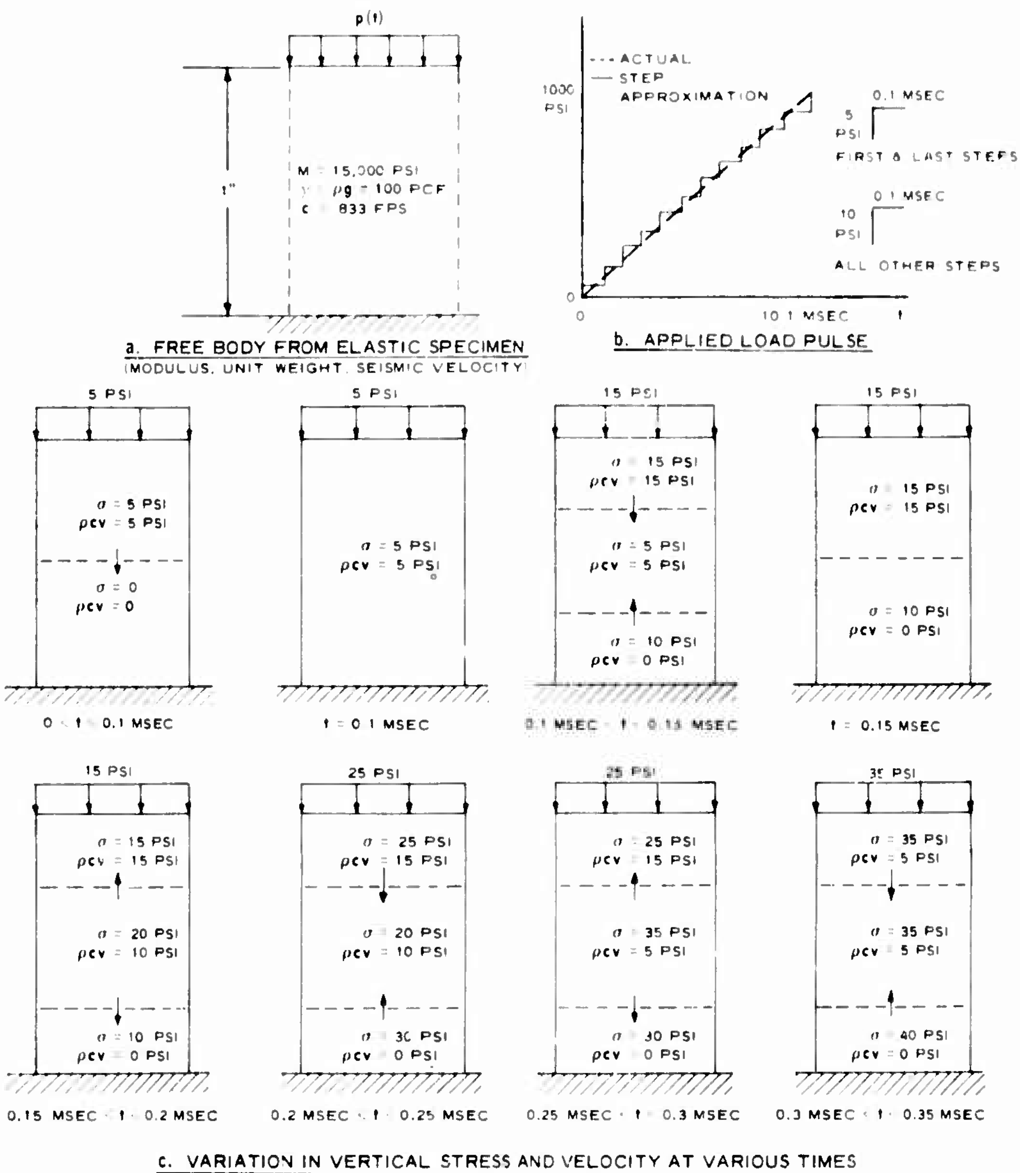


Fig. 5. Behavior during idealized test implementing multiple-reflection technique (from Whitman, 1963).

are considered in a separate discussion in the following section (Section 2.3). The two problems which do not specifically pertain to the details of the load-application system are considered below.

One of the general-type problems characteristic of the multiple-reflection technique is the interdependence between the specimen thickness and the upper bound for rate of load application. Since the interdependence stems from the very nature of the testing technique (see discussion above), it must be accepted; fortunately, for most conditions of interest, the problem has no practical application (see Section A.1).

It is apparent from the discussion above that, for a given specimen thickness (L), the upper bound for the rate of load application (σ_{max}/t_r) depends on the characteristic specimen wave velocity (U), the specimen mass density (ρ), and the maximum stress difference considered to be tolerable ($\Delta\sigma$, expressed as a percentage of the peak stress value, $\Delta = 100\Delta\sigma/\sigma_{max}$). The governing relationship can be written by inspection:

$$t_r \geq \frac{100}{\Delta}\frac{L}{U} \qquad (2.1)$$

The relationship can also be written in terms of the characteristic compression modulus (M), the acceleration of gravity (g), and the specimen unit weight (γ):

$$t_r \geq \frac{100}{\Delta}\sqrt{\frac{L^2\gamma}{gM}} \qquad (2.1)$$

It should be noted that the characteristic wave velocity (U) and the characteristic modulus (M) are readily determined only for linear-elastic material response; the wave velocity is the seismic velocity (c), and the modulus is the constrained modulus of deformation (M_c). The methods which

could be used to determine these quantities for materials with complex response characteristics cannot be described without considering the theories of one-dimensional wave propagation which pertain to the materials of interest, a subject clearly beyond the scope of this report.

The second general-type problem characteristic of the multiple-reflection technique is the restriction on equipment deformations (or equipment compressibility). The major implication of this restriction, which stems directly from the use of an indirect measurement to determine vertical strain in the specimen, is that it causes a number of disturbing detail-type problems in connection with equipment design (see discussions below and in Sections 3.5 and 4.4). Since the problem can be circumvented entirely by measuring the equipment deformations and compensating for them, it has little significance with regard to overall facility capabilities.

Equipment compressibility becomes a problem to consider whenever the vertical specimen strains are determined from a measurement of the displacement of the upper specimen surface. Since the displacement sensor is unable to differentiate between displacements which result from specimen compression and those which result from equipment deformations, the specimen-deformation determination is in error by an amount equal to the deformation of the contributing equipment components.

The equipment components whose deformations contribute to the error in the specimen-deformation determination are those which lie in the load-support system between the displacement sensor and the reference relative to which the displacement is made. If the reference is fixed in space (Fig. 4), all equipment components in the load-support system which lie beneath the displacement sensor contribute to the error.

Theoretically, the source of the error can be eliminated by locating the reference relative to which the displacement is made in the lower specimen boundary directly beneath the displacement sensor. Although the reference point can be placed in the desired location, it is not generally possible to bring the sensor (or an element rigidly fixed to it) to the vicinity of the reference in this location without adversely affecting other aspects of equipment performance. As a practical matter, therefore, it is generally necessary to locate the reference for the displacement measurement at a point fixed in space or at a convenient position on the equipment (see Section 2.3). In either case, there is an error in the specimen-deformation determination which requires consideration.

2.2.4 Other Techniques

The results of the literature review showed that two of the testing techniques which had been or were being used to determine the one-dimensional compression characteristics of soils for nuclear-weapons-effects applications were of special interest--the wave-propagation technique, because it was considered to be most appropriate for the general-purpose test facility to be developed, and the multiple-reflection technique, because it was found to be suitable for use in connection with such a test facility. Consequently, the characteristics of these two techniques were reviewed in some detail above. The other techniques which were described in the literature were found to be unsuitable for use in connection with a general-purpose test facility, as mentioned earlier. The characteristics of these techniques and their limitations are reviewed briefly below.

The Modified Conventional Technique. The technique used to determine the one-dimensional compression characteristics of soils for

conventional foundations and earthwork applications is described in all standard laboratory manuals devoted to soil testing (e.g., Lambe, 1951). The characteristics of the technique are generally similar to those shown in Fig. 4, with two important exceptions: (1) there is some provision for drainage of the pore fluid under load, and (2) the loading history consists of a number of increments, each of which is maintained until the observed deformation-time relationship becomes stable. (The initial "instability," generally referred to as consolidation, results from drainage of the pore fluid under load.) The modified conventional technique differs from the conventional technique in that drainage is not permitted. (The load is also occasionally applied continuously, instead of incrementally, as with the conventional technique.)

A test facility which implements the modified conventional testing technique is characterized by a number of features which are highly desirable in connection with general-purpose applications. An obvious and important feature is simplicity--in the characteristics of operation, in the nature of components, and in the interpretation of the data. There is also virtually no limitation either on specimen size or on peak-stress capability. In addition, the modified conventional technique is the only one which affords the opportunity for maintaining the zero-lateral-strain condition which characterizes the one-dimensional compression test; provisions are made for measuring the lateral strains as they occur throughout the test and compensating for them by the application of lateral stress (Hendron, 1963). (Other techniques can only limit the lateral strains to "tolerable" levels.)

The only major objection to the modified conventional technique,

as a technique, is its limitation in usefulness to soil materials whose response characteristics are not time sensitive; however, this limitation must be considered to be severe with regard to the intended application of the test facility considered herein (see Section 2.1). There are also a number of difficulties which stem not from the technique itself, but from the manner in which it is typically implemented. (An indication of some of these difficulties is provided in the discussion of the load-application system used at the University of Illinois test facility--Section 2.3). These difficulties, one of the most important of which is equipment compressibility, are particularly significant when equipment originally designed for conventional applications is used for nuclear-weapons-effects applications, where the requirements are somewhat different.

The Modified Wave-Propagation Technique. The modified wave-propagation technique appears to represent an attempt to combine the desirable features of the wave-propagation technique and the multiple-reflection technique. Thus, the applied load is permitted to propagate through the specimen, the specimen length required is only 1 or 2 feet, and buried gages are not required to measure specimen response (although buried gages may be used to obtain additional information, since these gages probably have little effect on the response of the overall specimen). The characteristics of the technique have been described by Durbin (1965), who refers to it as a wave-propagation technique. In essence, a step-type loading pulse with a rapid-rise portion is applied to the top of the specimen. As the pulse propagates through the specimen, each point is engulfed first by the rise portion and then by the dwell portion of the pulse; hence, the velocity at each point increases to an equilibrium value, after

which the velocity at the point becomes constant. When the wave front reaches the base of the specimen, the stress is constant throughout the specimen (except for the small portion near the base where the rise portion of the pulse is located). At this time, the load on the specimen and the displacement of the specimen surface can be measured, and a point on the stress-strain curve representing material response can be obtained. A series of tests is conducted to define the entire response.

The advantages of this testing technique are not clear. Although each point in the specimen is subjected to a rapidly changing stress environment as the wave front passes the point, the stress remains constant at the point for some period thereafter, during which time adjustments in material response resulting from time dependency can occur. Furthermore, in spite of the efforts expended to achieve wave propagation, the technique is still basically a static technique; at the instant the specimen response is measured, the entire specimen is in static equilibrium, albeit at a constant velocity.

In any case, the modified wave-propagation technique is not suitable for use in connection with a general-purpose test facility. The necessity of conducting a series of tests, rather than a single test, to define completely the response characteristics of the specimen clearly imposes an undesirable restriction on such a facility. Also, the technique produces meaningful results only if the material response characteristics are such that a stable shock can be formed and maintained throughout the specimen; this is unlikely to be the case--particularly for an unloading pulse--for most soils of interest (Whitman and Clark, 1964). (There are also a number of difficulties associated with each of the several equipment

and measurement-system designs which have been used to date--Zaccor, Mason, and Walter, 1964; however, these are too involved to be considered herein.)

The Shock Technique. A dynamic, one-dimensional compression testing technique which has been described in the literature in connection with tests on various types of rock specimens has been recommended for use in connection with soil specimens (Ainsworth and Sullivan, 1967). The applied load, in the form of a step pulse with an extremely rapid rise, is applied to one end of the test specimen. As the wave propagates through the specimen, the particle velocity-time relationship is measured at several locations in the specimen. With this information, one can deduce the stress-strain characteristics of the specimen by assuming that the pulse is propagated as a stable shock.

The technique is unsuitable for use in connection with the general-purpose test facility considered herein for a number of reasons. The difficulties associated with the use of buried gages have already been discussed. Although velocity gages of the type selected by Ainsworth and Sullivan (very thin wires in a magnetic field) are probably not a problem with regard to foreign-inclusion considerations, there are still the unavoidable difficulties associated with specimen disturbance resulting from gage placement. Another problem associated with the shock technique has already been discussed in connection with the modified wave-propagation technique--the impracticality of the stable-shock assumption, particularly for an unloading pulse, for most soils of interest. Rise-time restrictions represent still another problem in connection with general-purpose applications.

Sonic Techniques. A number of the testing techniques which

have been used to determine the compression response characteristics of soils under dynamic conditions can be referred to collectively as sonic techniques. These techniques have two common features: (1) the use of a very-low-amplitude stress; and (2) the presence of significant inertial stresses. The three principal types of sonic techniques described in the literature reviewed are the pulse-type sonic technique (Lawrence, 1961), the resonance-type sonic technique (Wilson and Dietrich, 1960), and the oscillatory-type sonic technique (Konder and Krizek, 1962).

These techniques are clearly unsuitable for use in connection with a general-purpose, one-dimensional compression test facility for nuclear-weapons-effects-related problems, since the limitation on peak-stress capability represents a severe restriction on the capability of a facility of this type. It is highly unlikely that the response characteristics determined from a test of the sonic type will accurately reflect the behavior of the material when it is subjected to the high-amplitude loads of interest in nuclear-weapons-effects-related problems; the mechanisms of response are completely different for the two types of loads, even though both are dynamic (see Section 3.1).

2.3 Loading Techniques

2.3.1 Introduction

The selection of the multiple-reflection technique as the one most suitable for use in connection with the general-purpose, one-dimensional compression test facility to be developed marked the first milestone in the investigation reported herein.

The next problem considered in the conceptual-design phase of

the investigation dealt with the selection of a technique for load application for the general-purpose test facility. The results of the literature review and facility evaluation studies conducted in support of the testing-concept design problem had shown that each of the test facilities which had already implemented the multiple-reflection technique was subject to a number of limitations which appeared to be directly related to the nature of the load-application system used. Consequently, it was thought to be desirable to devote some effort to the loading-concept design problem before undertaking the design of a specific facility.

The result of the effort was the formulation of a new concept for the load-application system. The various limitations associated with each of the test facilities implementing the multiple-reflection technique are reviewed below, and the relationship between these limitations and the nature of the load-application system used in each case is pointed out. The new concept for the load-application system and the advantages to be realized by its use are then discussed.

2.3.2 General Comments

A few general comments are presented below to facilitate the presentation of the discussions which follow.

Load Generation. Of all the various laboratory techniques used to generate the impulse-type loading pulses characteristic of the air blast and ground shock from a nuclear explosion, the one which affords the most opportunity for control of the characteristics of the applied loading is the cold-gas-expansion technique. Other major techniques include the hot-gas-expansion technique (or explosion) and the projectile or impact technique.

The cold-gas-expansion technique is fairly simple in principle,

although the degree of its success is highly sensitive to the details of its implementation. For the loading portion of the pulse, a large volume of pressurized gas is collected behind a rapid-acting valve (e.g. solenoid, frangible diaphragm); when the valve is opened, the high-pressure gas expands into a volume which is small relative to its original volume, and the required rapid rise is achieved.

For the unloading portion of the pulse, another rapid-acting valve is opened, and the high-pressure gas is permitted to escape. Frequently, a special rapid-acting valve is used for the unloading portion to accelerate the rate of decay beyond that which can be achieved by simple release (see, for example, Cunny and Sloan, 1961).

The actual load generation may be effected either in the vicinity of the specimen or inside a dynamic loading machine (which then transmits the short-duration load to the specimen). The former technique is referred to herein as fluid loading, and a test facility which incorporates this technique is referred to as a fluid-loading facility. The latter technique is referred to herein as piston loading, and a test facility which incorporates this technique is referred to as a piston-loading facility.

Measurements. The discussions above have already considered some of the several different types of measurements which can be used to provide the data required. These measurements are made by electromechanical transducers, which convert the given mechanical input signals sensed into proportional electrical output signals in the form of voltage. The voltages are amplified as necessary and are recorded automatically as a function of time. In general, the recording equipment and transducers used are

commercial items, and their characteristics and principles of operation are described in detail in the Shock and Vibration Handbook (Harris and Crede, 1961).

2.3.3 Fluid Loading

The development of one-dimensional compression test facilities which incorporate fluid loading in conjunction with the multiple-reflection testing technique has been reported by three organizations--Massachusetts Institute of Technology (MIT), Stanford Research Institute (SRI), and the Eric H. Wang Civil Engineering Research Facility of the University of New Mexico (CERF). The MIT facility was the first to be developed (Whitman et al., 1959); it has the additional distinction of having been the first one-dimensional compression test facility of any type developed specifically for nuclear-weapons-effects applications. This facility, as it was first reported, is shown schematically in Fig. 6. Subsequent modifications to the original design concept resulted in a series of improvements to the MIT facility (Whitman, Roberts, and Mao, 1960; Healy, 1960; Moore, 1961; Whitman, 1963, Moore, 1963) and in the development of similar facilities at SRI (Seaman and Whitman, 1964; Seaman, 1966) and CERF (Calhoun and Kraft, 1966). Drawings of the MIT, SRI, and CERF facilities, as they were most recently reported, are shown in Figs. 7, 8, and 9, respectively; photographs of the three facilities appear in Fig. 10.

Although there are some differences in detail between the three facilities, their general characteristics are very similar. In each case, the basic assembly or device contains two principal components--a soil container and a fluid container--which, when bolted together, form a

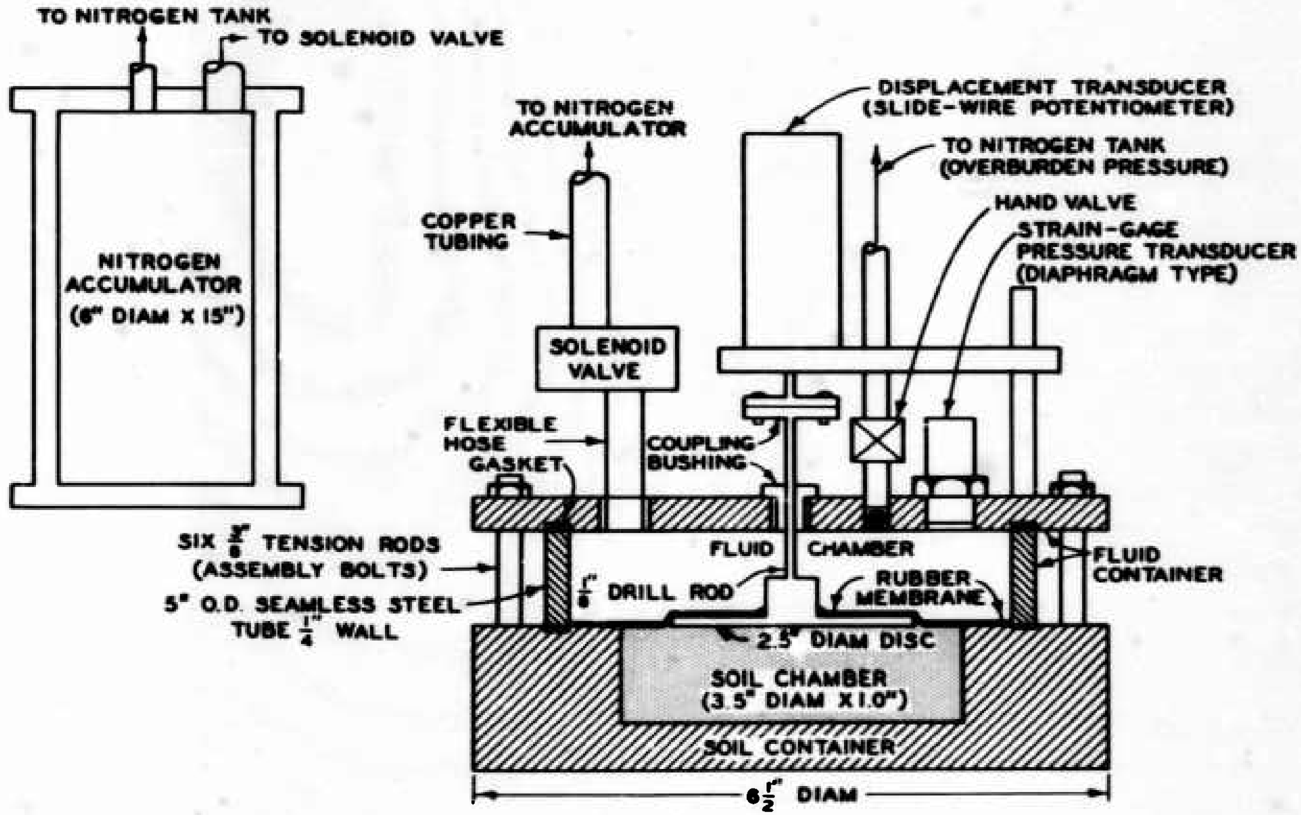


Fig. 6. First test facility designed for nuclear-weapons-effects applications (from Whitman et al., 1959).

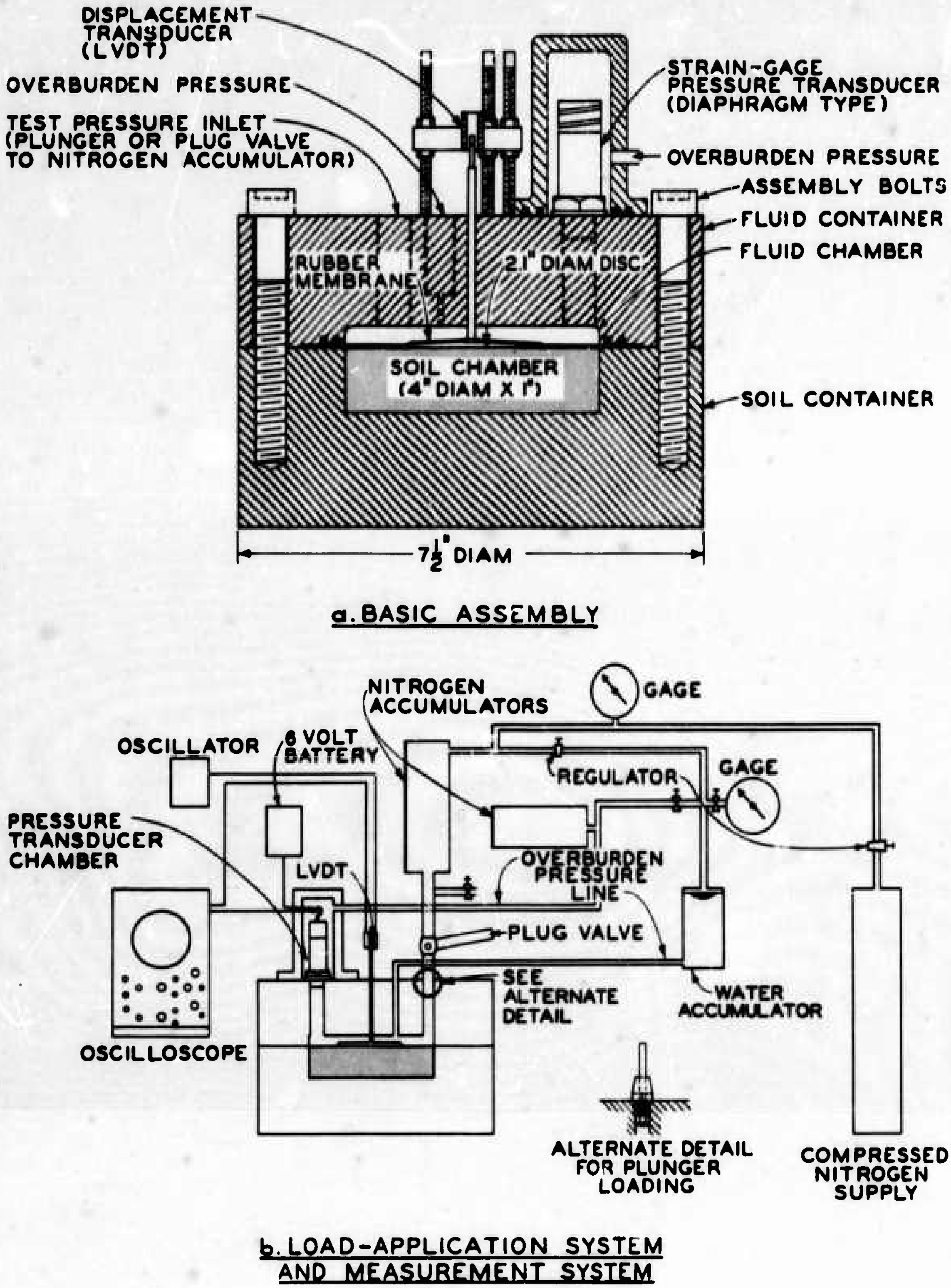


Fig. 7. Key elements in MIT test facility (from Moore, 1963).

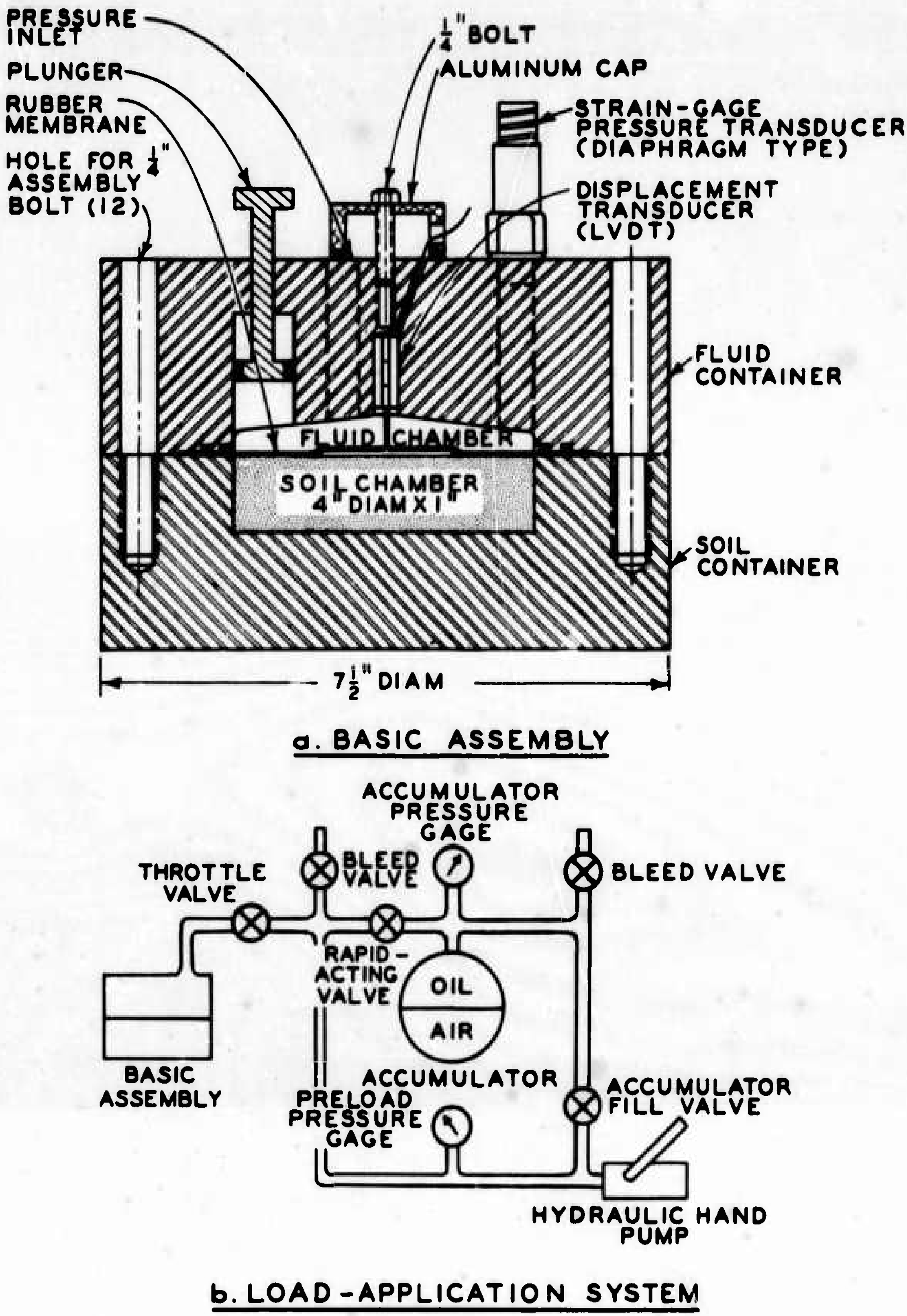


Fig. 8. Key elements in SRI test facility (from Seaman, 1966).

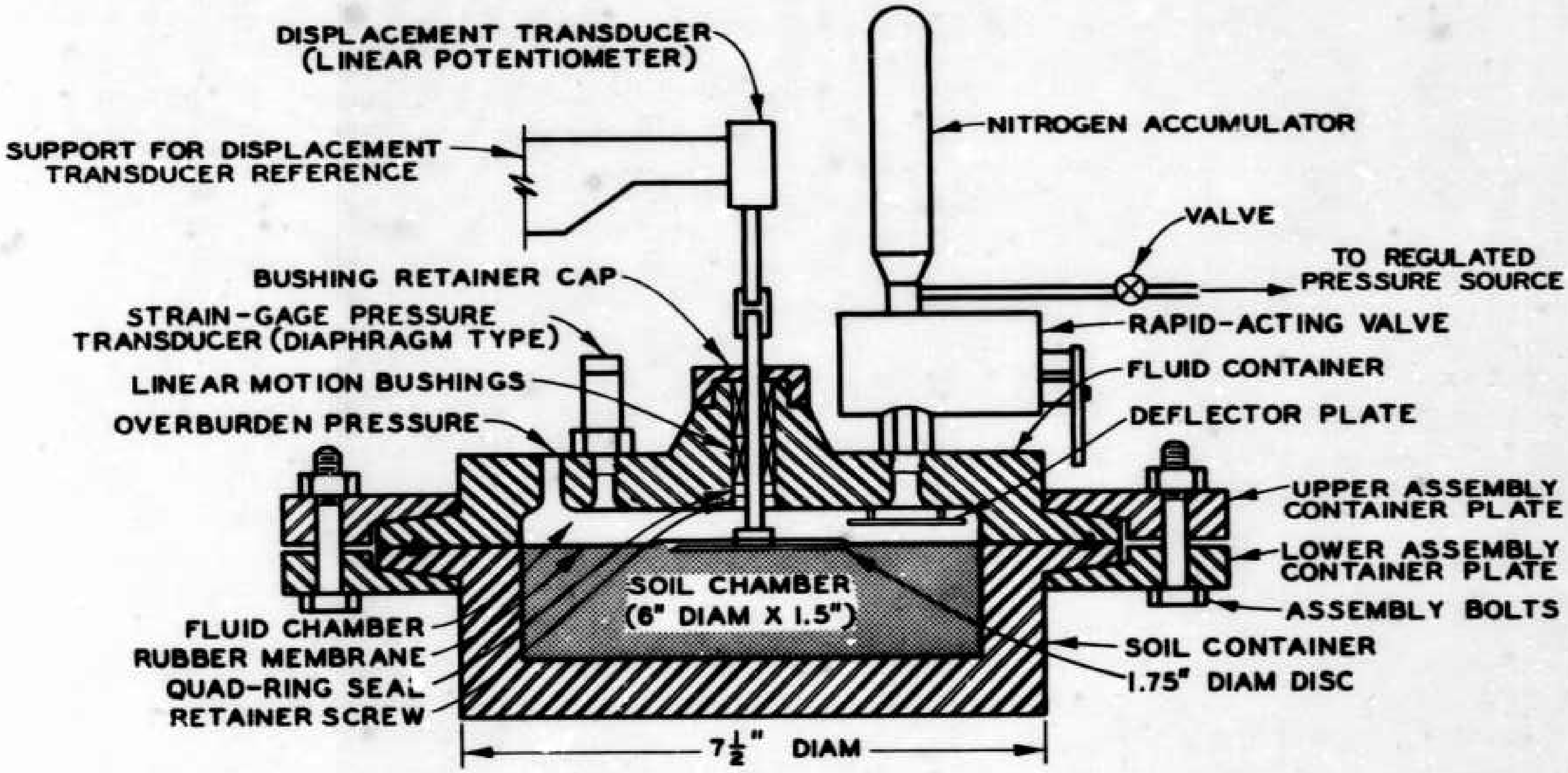
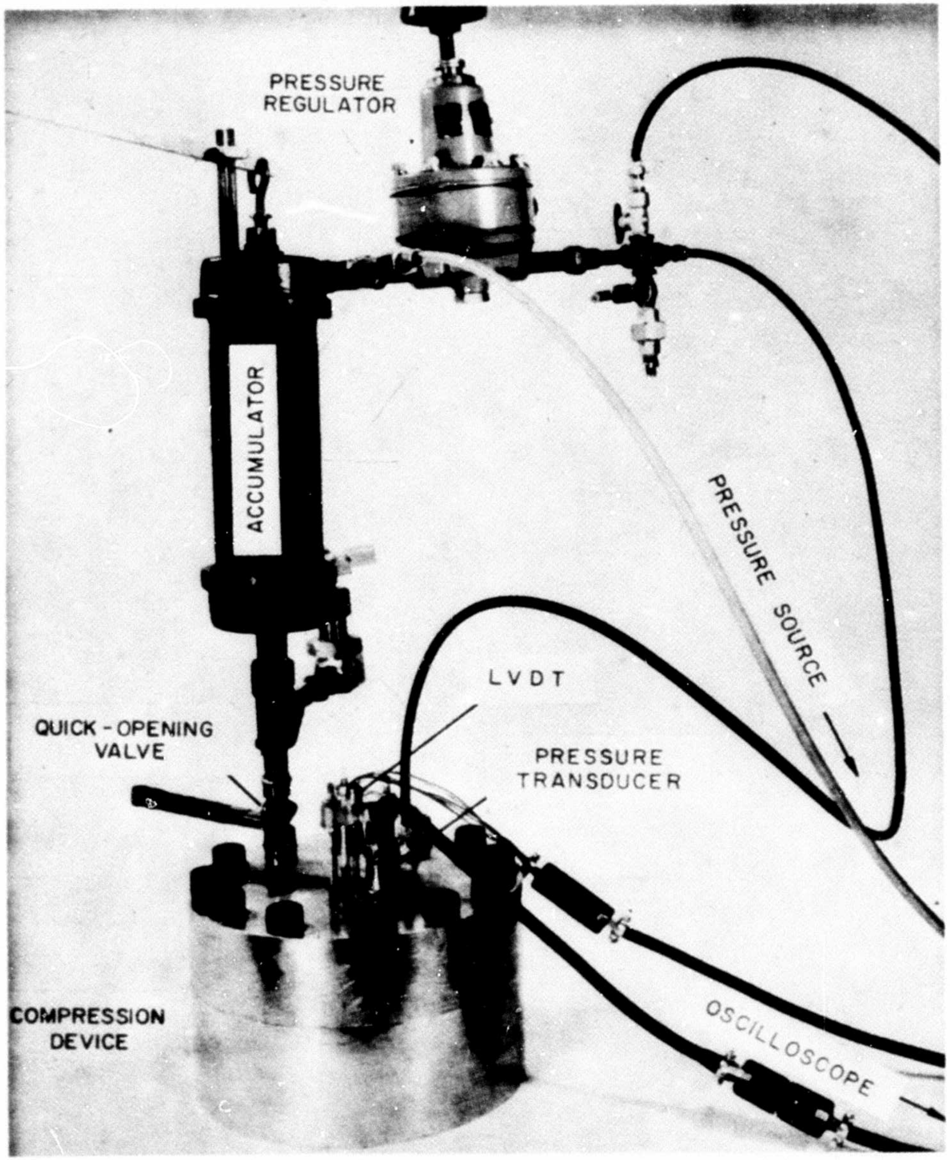
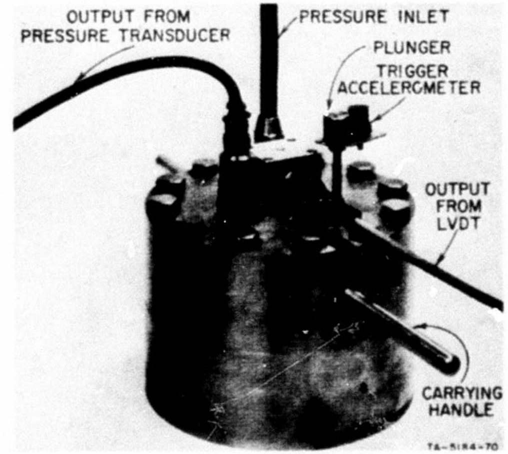


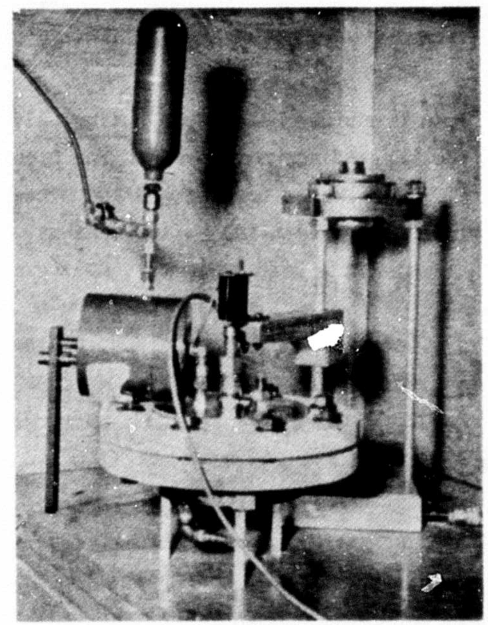
Fig. 9. Key elements in CERF test facility (from Calhoun and Kraft, 1966).



a. MIT equipment



b. SRI equipment



c. CERF equipment

Fig. 10. MIT, SRI, and CERF equipment (from Moore, 1963; Seaman, 1966; and Calhoun and Kraft, 1966).

sealed pressure chamber. Load is applied directly to this pressure chamber by the cold-gas-expansion technique. The fluid chamber, which is isolated from the soil chamber by a flexible rubber membrane, is hydraulically connected to a large volume of pressurized nitrogen through a rapid-acting valve; when the valve is suddenly opened, the pressurized nitrogen expands against the rigid hydraulic fluid (water or oil) which in turn loads the specimen. (The function of the rigid fluid is to reduce the volume into which the pressurized nitrogen must expand and thereby to reduce the loading duration.) In two of the facilities, even shorter loading durations can be achieved by manually striking a plunger which impulsively loads the rigid fluid in the fluid container. Vertical stress in the specimen is determined by measuring the pressure in the fluid chamber; vertical strain in the specimen is determined by measuring the displacement of the central portion of the specimen surface, where effects of sidewall friction are relatively unimportant.

Careful examination of the test facilities depicted in Figs. 7 through 10 showed that there were a number of difficulties associated with their use for general-purpose applications. Many of these difficulties stem directly from the nature of fluid loading; others stem only in part from the nature of the load-application system, and a few are independent of the load-application system. Only those difficulties which are in some way related to fluid loading are of direct interest at present, and consequently only those are considered below.

It is important to recognize that the significance of the various difficulties discussed below cannot be precisely evaluated. In all likelihood, some of the difficulties result in relatively insignificant

errors in the details of the stress-strain curve obtained; others result in important errors. Some of the difficulties result in important errors--or limitations--only under certain conditions, such as for stiff, undisturbed specimens or for very short-duration loadings. In any case, the intent herein is not to provide a critical evaluation of the facilities themselves, but rather to call attention to the types of problems and limitations which appear to be associated with the fluid loading technique.

One of the difficulties which can be recognized readily is that the load is not applied uniformly to the surface of the specimen. As a result, shear waves may propagate through the specimen and destroy the state of one-dimensional compression desired. Furthermore, both the pressure measurement and the displacement measurement may be somewhat in error, the pressure measurement as a result of the time lag in the remote sensor and the displacement measurement as a result of tilting of the core rod. (The LVDT, linear-variable-differential-transformer, used in the MIT and SRI facilities is sensitive to tilting.) Although small-diameter specimens can be used to minimize the significance of these difficulties, this in turn places a severe restriction on the capabilities of the facility. In addition, limiting the maximum specimen diameter also limits the maximum specimen thickness, since the two are related by sidewall-friction considerations, and thin specimens can be highly undesirable. Trimming and seating errors are very important for such specimens, particularly for relatively rigid sampled specimens. Furthermore, it is frequently difficult to measure accurately the small displacements which the surfaces of such specimens undergo because normal mechanical and electrical noise distort the signal, and because calibrations cannot be made in the small-displacement

range with equipment ordinarily available.

Another difficulty which stems directly from the nature of fluid loading is the restriction on the amount of control which can be exercised on the time characteristics of the applied loading pulse, particularly the unloading portion. Because the expanding gas (or the rigid fluid which it compresses) is in intimate contact with the soil specimen, the special control valves required cannot be installed conveniently in the particular locations where their implementation would be most effective. Such a restriction is clearly an important consideration for research applications. It is also somewhat limiting for practical applications, particularly when the soil of interest has significantly time-dependent constitutive characteristics.

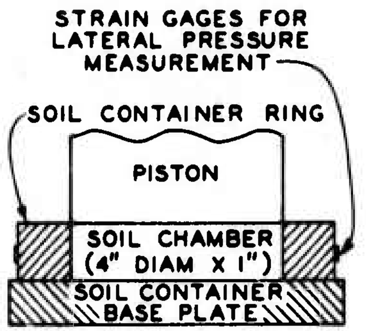
One other important difficulty observed stems from a conflict in the requirements of the load-application system and the measurement system. Since it is necessary to have the sensing element for the displacement measurement at the specimen surface and highly desirable to have a fixed reference point outside the pressure environment, the sensing element must pass from inside the fluid container where it senses the movement of the specimen to outside the fluid container where it relates this movement to a fixed reference point. If the passage point is not sealed (MIT facility), uncontrolled pressure leakage occurs; if it is sealed (CERF facility), there is some restriction on the ability of the measurement system to follow the movement of the specimen surface. If this conflict is resolved by placing the fixed reference point inside the pressure environment (SRI facility), it is not possible to guarantee the "fixity" of the reference, nor is it possible to calibrate the transducer under the pressurized

environments in which it is actually used. In addition, there is some sacrifice in the versatility of the facility, since it is possible to "null" the displacement transducer (i.e., set it at zero) only once for each test. This can result in inaccurate displacement measurements if the seating displacements are large relative to the test displacements, or if a test with several loading cycles is required.

2.3.4 Piston Loading

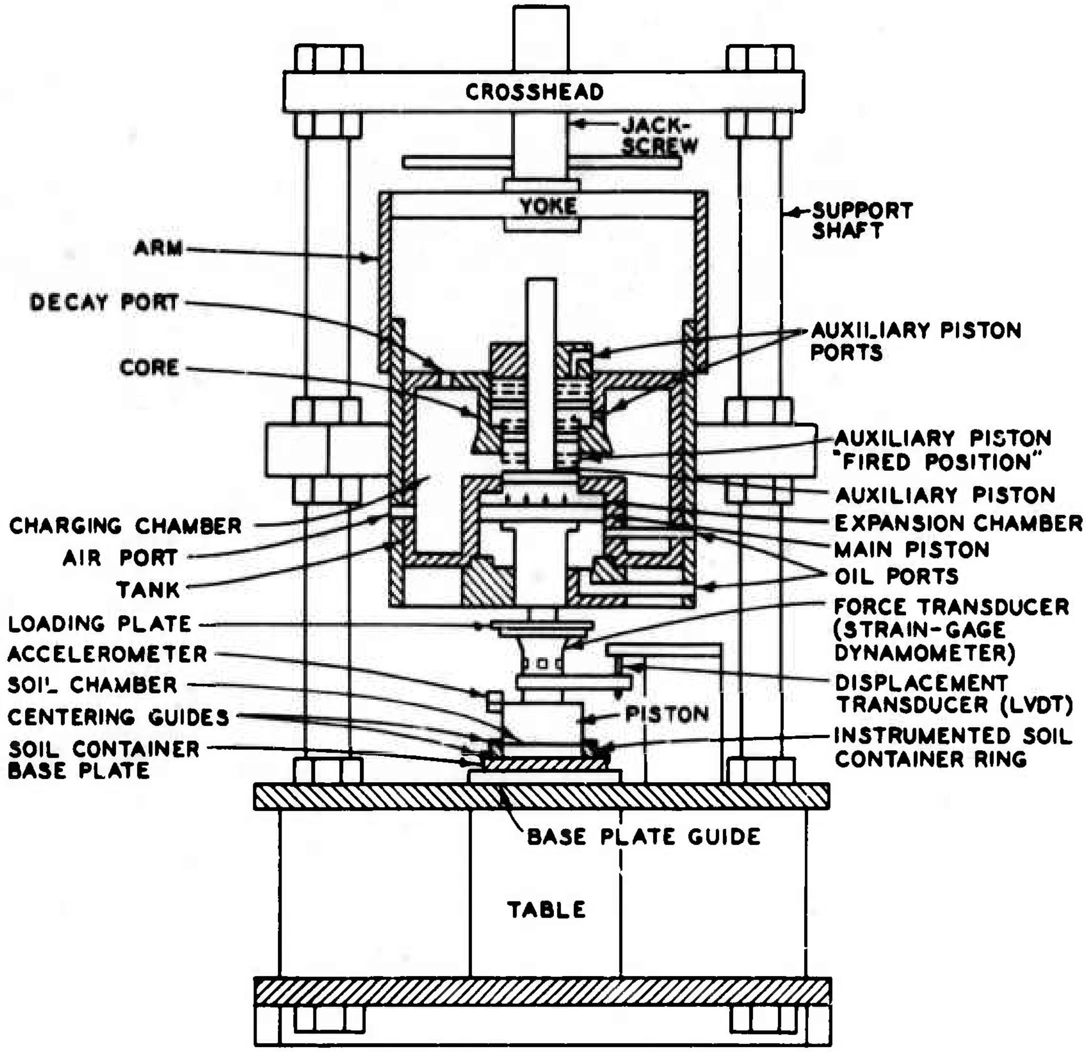
Unlike the test facilities described above, the one-dimensional compression test facility developed at the University of Illinois (UI) for nuclear-weapons-effects applications incorporates the piston-loading technique (Kane, Davisson, Olson, and Sinnamon, 1964; Davisson, Maynard, and Koike, 1965). A drawing of the UI facility, as it was most recently reported, is shown in Fig. 11; photographs of the facility appear in Fig. 12.

The basic assembly (Fig. 11) is the same as that used in nearly all test facilities developed for the purpose of determining the one-dimensional compression characteristics of soils for conventional applications. (The fluid-loading technique has been used only in one or two cases in connection with conventional soil testing--Rowe and Barden, 1966.) Loading pulses of the type required for nuclear-weapons-effects applications are generated inside one of several available dynamic loading machines, each of which uses the cold-gas-expansion technique to suddenly accelerate a load column or ram against a rigid piston placed over the soil specimen. Vertical stress in the specimen is determined by measuring the force in the load column above the specimen; vertical strain in the specimen is determined by measuring the displacement of the piston which is in contact with the specimen surface.



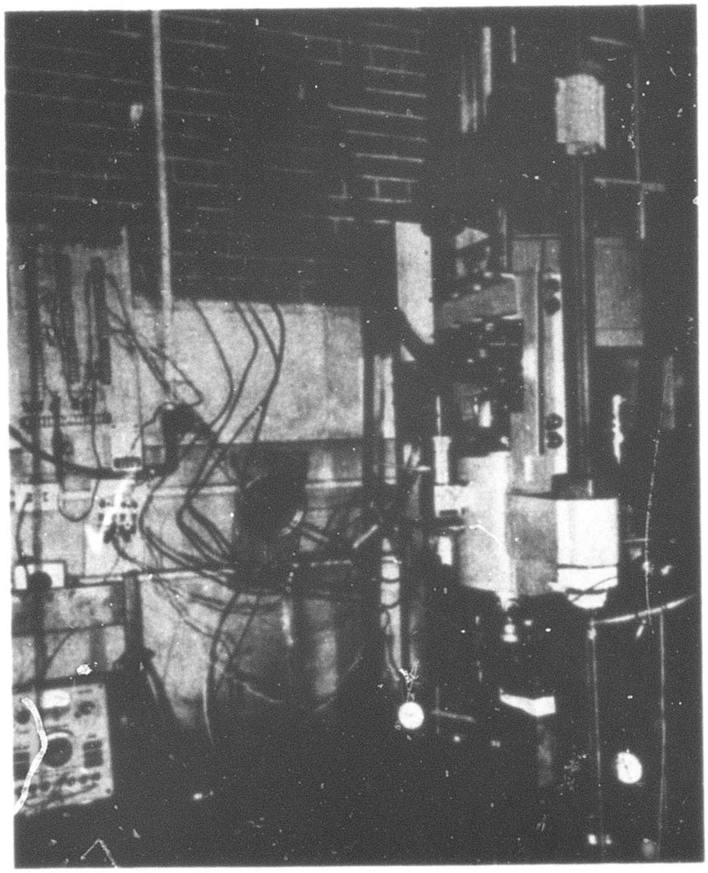
a. BASIC ASSEMBLY

NOTE: THE 10-KIP LOADER SHOWN BELOW IS ONE OF THREE AVAILABLE LOADING MACHINES, THE OTHER TWO BEING A 200-KIP MACHINE SIMILAR TO IT AND A 125-KIP HYDRAULIC-RAM LOADER.

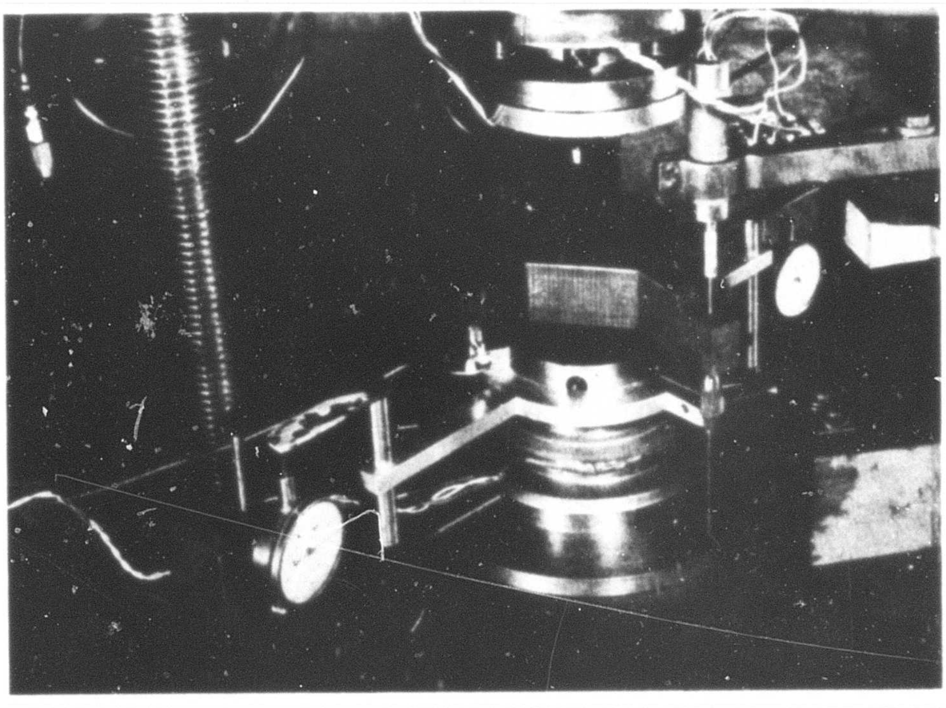


b. 10-KIP DYNAMIC LOADING MACHINE

Fig. 11. Key elements in UI test facility (from Davisson, Maynard, and Koike, 1965).



a. Overall view of 10-kip dynamic loading machine



b. Closeup view of basic assembly

Fig. 12. Photographs of some of the UI equipment (from Davisson, Maynard, and Koike, 1965).

Although the loading technique used has the distinct advantage of affording an opportunity for control of the time characteristics of the applied loading pulse, it leads to a rather undesirable test configuration. (It is perhaps for this reason that the piston-loading technique has not been used elsewhere.) As soon as load is transferred to the specimen by the piston, some soil squeezes into the annular space between the piston and the soil-container ring and, when a two-piece soil container is used (as in the UI facility), into the space between the soil-container ring and the soil-container base plate. (When a two-piece soil container is used in a fluid-loading facility, the soil-container ring is loaded by the applied pulse, and the squeezing tendency of the soil is restricted.) The lost soil certainly is reflected as an error in the displacement measurement. In addition, that portion of the soil which squeezes into the space between the piston and the ring may cause the piston to bind somewhat, resulting in a transfer of load from the piston to the soil-container ring. Since the force transducer measures the total force above the piston and not the load which reaches the soil, an error is made in the force measurement. There is an even more important load transfer which is not observed by the remote force transducer--the transfer of load from the specimen to the soil-container wall by sidewall friction. This load transfer not only results in an error in the force measurement, but also in nonuniform loading conditions throughout the specimen (since the rigid piston forces the entire surface of the specimen to deform uniformly).

If the desired loading duration is very short, piston loading results in some additional difficulties. Since very short load durations can be achieved only by high load-column accelerations, which result in

large inertial forces throughout the column, force in the transducer under such conditions is not necessarily equal to force in the specimen, and the measurement is in error. An attempt can be made to correct the force measurement for the inertia of the mass between the transducer and the specimen by measuring the acceleration of this mass; however, this type of correction is approximate at best. High load-column accelerations also cause considerable "overshoot" of the programmed load and high-frequency components of load throughout the pulse, which result in nonuniform loading conditions in the specimen (as a function of depth in the specimen) and complications in data reduction.

2.3.5 Piston-Fluid Loading

It is apparent from the discussions above that the use of both the fluid-loading technique and the piston-loading technique has resulted in a number of difficulties and restrictions in the various nuclear-weapons-effects-oriented, one-dimensional compression test facilities which have implemented the multiple-reflection testing technique. It is interesting to note, however, that the most serious difficulties associated with each of the testing techniques are eliminated when the other technique is used. Fluid loading causes no problems at the upper specimen surface, and piston loading affords the opportunity both for uniform loading and for control of the time characteristics of the applied loading pulse. It should be possible, therefore, to formulate a new, improved concept for load application by simply combining the more desirable features of each of the two loading techniques already in use.

There should be little or no difficulty in implementing a

combined or piston-fluid loading technique. Component details are more appropriately considered in connection with the design of a specific installation, and consequently need not be considered at present. General component characteristics can readily be visualized by simply combining the components required for implementation of each of the techniques separately. If, for example, the basic assemblies of the CERF and UI test facilities were to be combined, the resulting basic assembly would be similar to that shown schematically in Fig. 13. (The transition configuration required to transfer load from the load column of a dynamic loading machine to the piston could take several forms, and it should not present any serious problems in the design of a specific installation.)

It is apparent from Fig. 13 that piston-fluid loading does not eliminate the problem which stems from the conflicting requirements of the load-application system and the measurement system (discussed above in connection with fluid loading). It is equally apparent, however, that all the other difficulties discussed in connection with both fluid loading and piston loading are eliminated when the piston-fluid loading technique is used. The load is applied uniformly to the entire specimen surface; the use of a dynamic loading machine makes it possible to control the time characteristics of the applied loading pulse, and there are no complications at the upper specimen surface. Consequently, it appears that the combined piston-fluid loading technique would be a far better selection for the general-purpose, one-dimensional compression test facility to be developed than either the fluid-loading technique or the piston-loading technique.

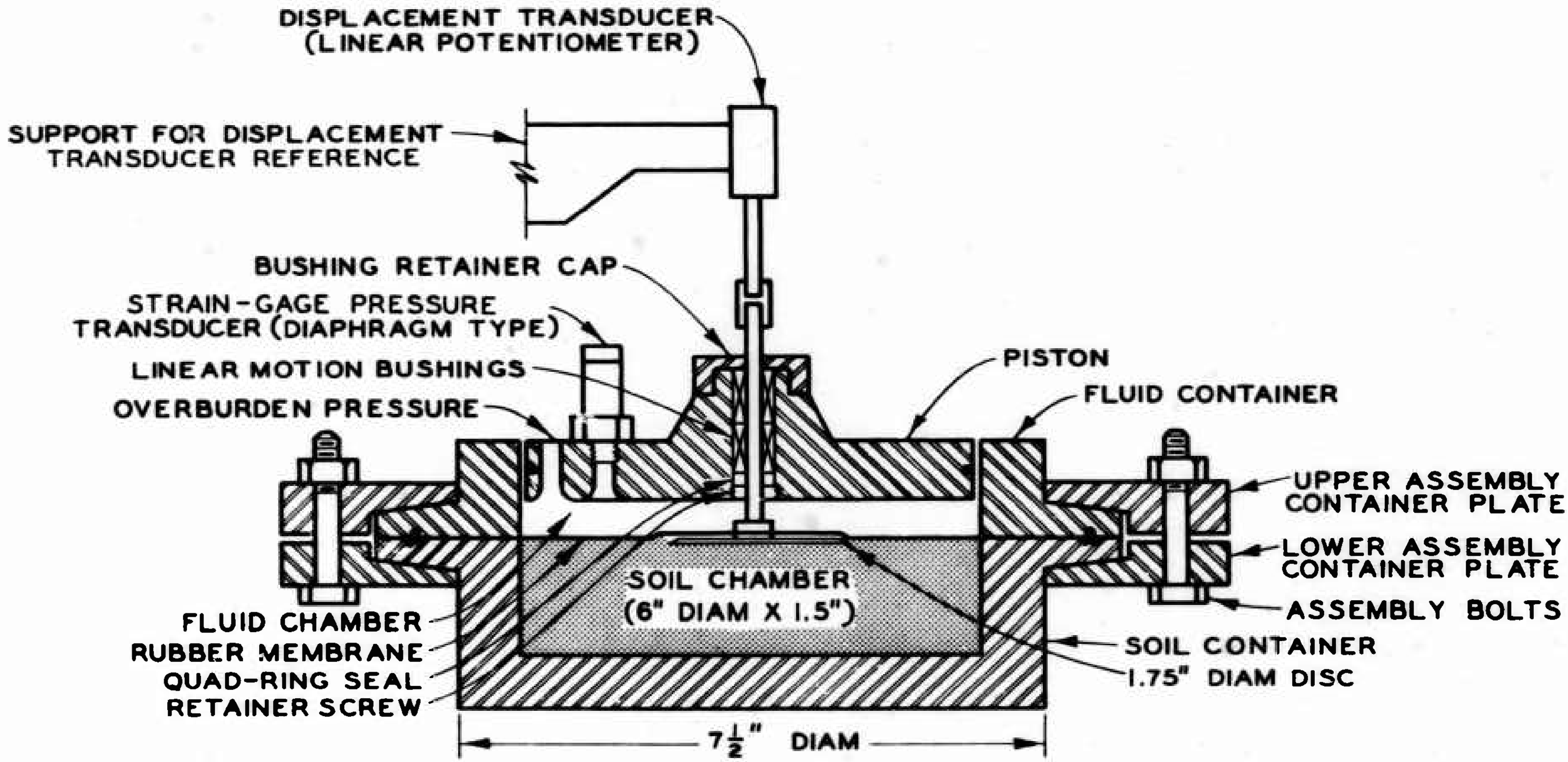


Fig. 13. Key elements in hypothetical combined loading test facility.

CHAPTER 3

DESIGN CONSIDERATIONS

3.1 Introduction

3.1.1 General

The major objective of the investigation described herein was to develop a general-purpose, one-dimensional compression test facility which could be used to provide soil-property data in support of a host of diverse nuclear-weapons-effects-related activities. The conceptual-design phase of the investigation, as described in Chapter 2, resulted in the selection of the gross features of the test facility. The specific considerations involved in the actual detailed design of the general-purpose device and all associated appurtenances are described below.

The first step in the detailed-design phase of the investigation was the selection of a location for the test facility. The matter was discussed with personnel of the U. S. Army Engineer Waterways Experiment Station (WES), who had been instrumental in bringing to the attention of the author the problem which generated the investigation (Section 1.2), and an agreement was reached whereby the test facility would be designed, fabricated, installed, and evaluated at WES, where a substantial portion of the Defense Atomic Support Agency-sponsored, nuclear-weapons-effects research program was already being conducted.

The various considerations involved in the design of the general-purpose, one-dimensional compression test facility for WES are discussed below in terms of the four principal components which comprise the facility (Sections 3.3, 3.4, 3.5, and 3.6). Because one of the major

objectives of the investigation was to provide an insight into the various factors which affect the experimental-accuracy capability of the test facility (Section 1.3), the discussions presented are fairly comprehensive in scope. Whenever an originally designed element (or group of elements) was found to be unsuitable, both the design of the original element and the design of the modified element are discussed. Reasons for the modifications are generally discussed in Chapter 4, which deals with the comprehensive experimental program undertaken to evaluate the device and its various appurtenances.

The discussions dealing with the specific design considerations for the elements which comprise the four principal components of the test facility are preceded by a general discussion which describes the entire equipment assembly (Section 3.2). It should be noted that two different test configurations were designed for the equipment in order to facilitate the experimental evaluation program; furthermore, the originally designed equipment configurations were subsequently found to be unsuitable, and they were replaced by modified configurations. Since the general discussion dealing with the entire equipment assembly provides the framework for the more detailed design discussions which follow, descriptions of all the equipment configurations used are included in Section 3.2.

3.1.2 Specifications for Design

The specifications upon which the design of the WES one-dimensional compression device and its appurtenances was based are summarized below. These specifications, which were prepared by the author in coordination with WES, represent an attempt to incorporate both WES's

requirements and the immediate and ultimate objectives of this investigation into a single set of governing criteria.

General guidance for the design considerations was provided by the following four specifications:

(1) Accuracy Range: ±10 percent for routine tests to ±5 percent for special tests as required.

(2) Peak-Pressure Range: 1 to 1000 psi, with emphasis on the 100- to 1000-psi range.

(3) Rise-Time Range: As fast as possible to static.

(4) Specimen-Stiffness Range: Constrained moduli from 4000 to 200,000 psi at a pressure of 1000 psi.

The specification dealing with the accuracy of the data was expressed in terms of the final result. To insure that an overall accuracy of ±5 percent could be achieved, a criterion of ±1 percent was established for each of the individual elements in the design.

Although no value was specified for the minimum rise time to be achieved, a value of 3 msec was used in the design considerations. This value was considered to be a lower bound, in that even if shorter rise times could be obtained they would not be useful (see Section A.1).

3.2 General Configuration

3.2.1 Principal Configuration

The first step in the design procedure was to select a configuration for the device which would be most likely to satisfy the stated specifications and which would be well suited to the intended use of the

general-purpose facility. The configuration selected is reflected in a drawing of the device as it was originally designed and built, Fig. 14.

The original device shown consists of a soil container, a fluid container, a pair of assembly container plates (upper and lower), a piston assembly, a load-column adapter, a support structure for the zero-reference portions of the displacement transducers (LVDT's), and a set of LVDT core housings.

The purpose of the soil container is to contain the soil specimen (i.e., to prevent the escape of both soil particles and pore fluid) under load and to provide the specimen with a lateral boundary which is capable of maintaining the no-lateral-strain condition that characterizes the one-dimensional compression test. The purpose of the fluid container is simply to contain the loading fluid. Three of the four equally spaced holes through the fluid-container wall are for hydraulic purposes, and are terminated by sealed fittings and valves. One of these, which can be seen in Fig. 16, serves as an inlet for the pressure fluid; the other two are used for the differential pressure transducer line (Section 3.6). The fourth hole, which is also visible in Fig. 16, contains the flush-mounted pressure transducer (Section 3.6). The function of the assembly container plates is to make it possible to clamp the fluid container to the soil container--thereby compressing the O-ring at their interface and sealing the pressure chamber--without the somewhat undesirable condition of having large-diameter holes in the soil-container ring. The piston assembly--which includes the upper piston, the lower piston, and the three assembly columns--and the load-column adapter constitute the load-application system in that they provide the transition configuration required to transfer load

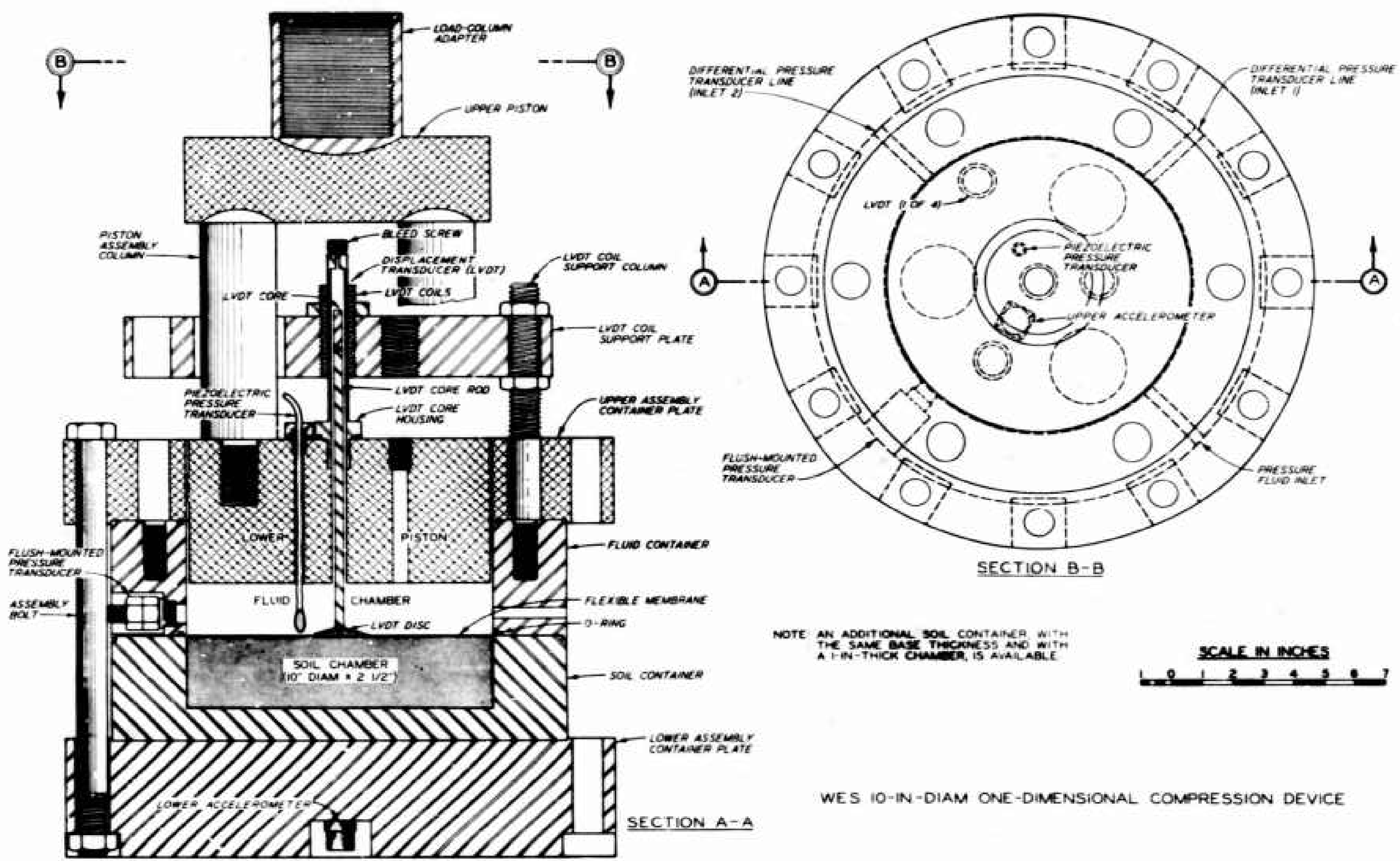


Fig. 14. Drawing of basic assembly for original principal configuration.

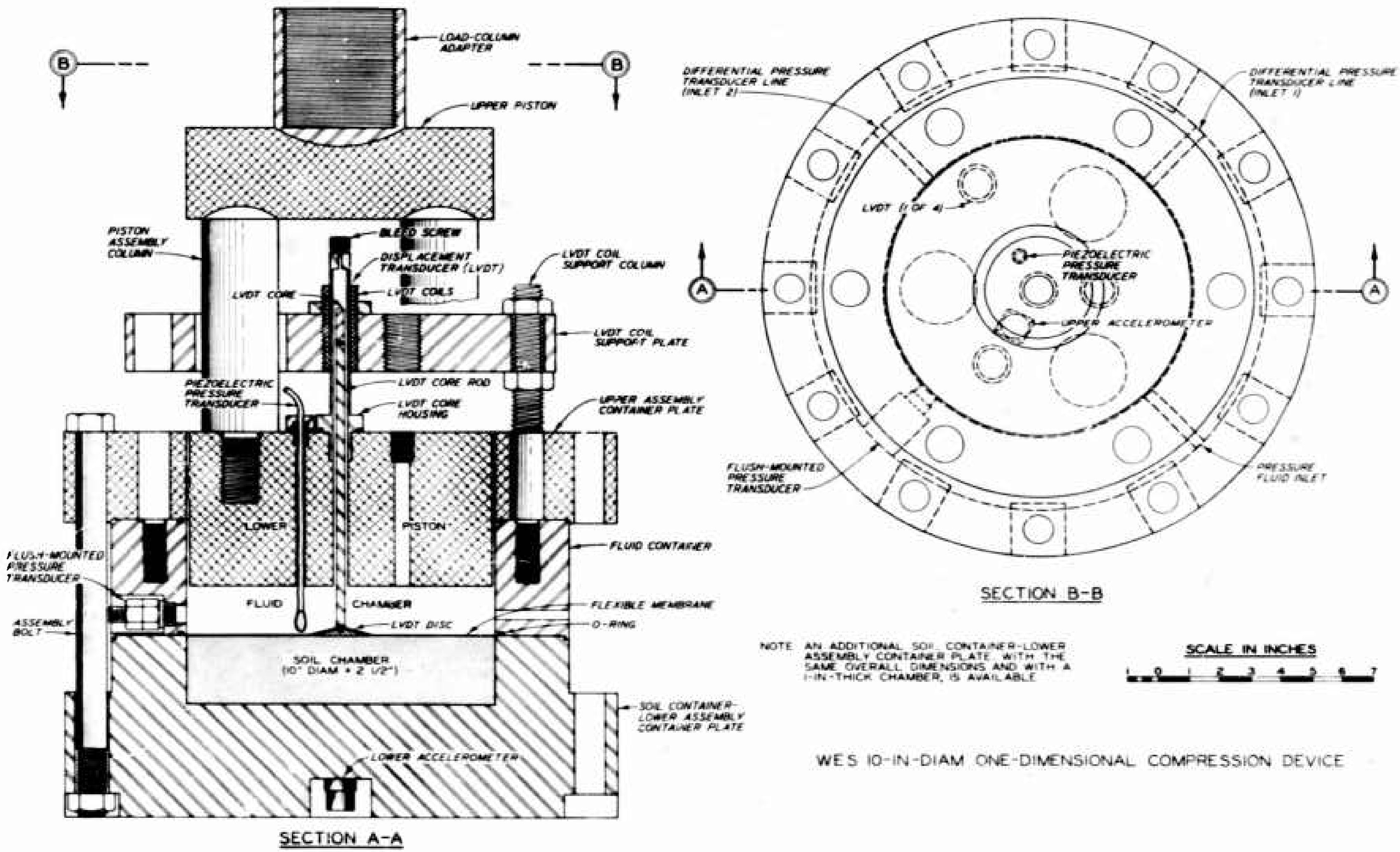


Fig. 15. Drawing of basic assembly for modified principal configuration.

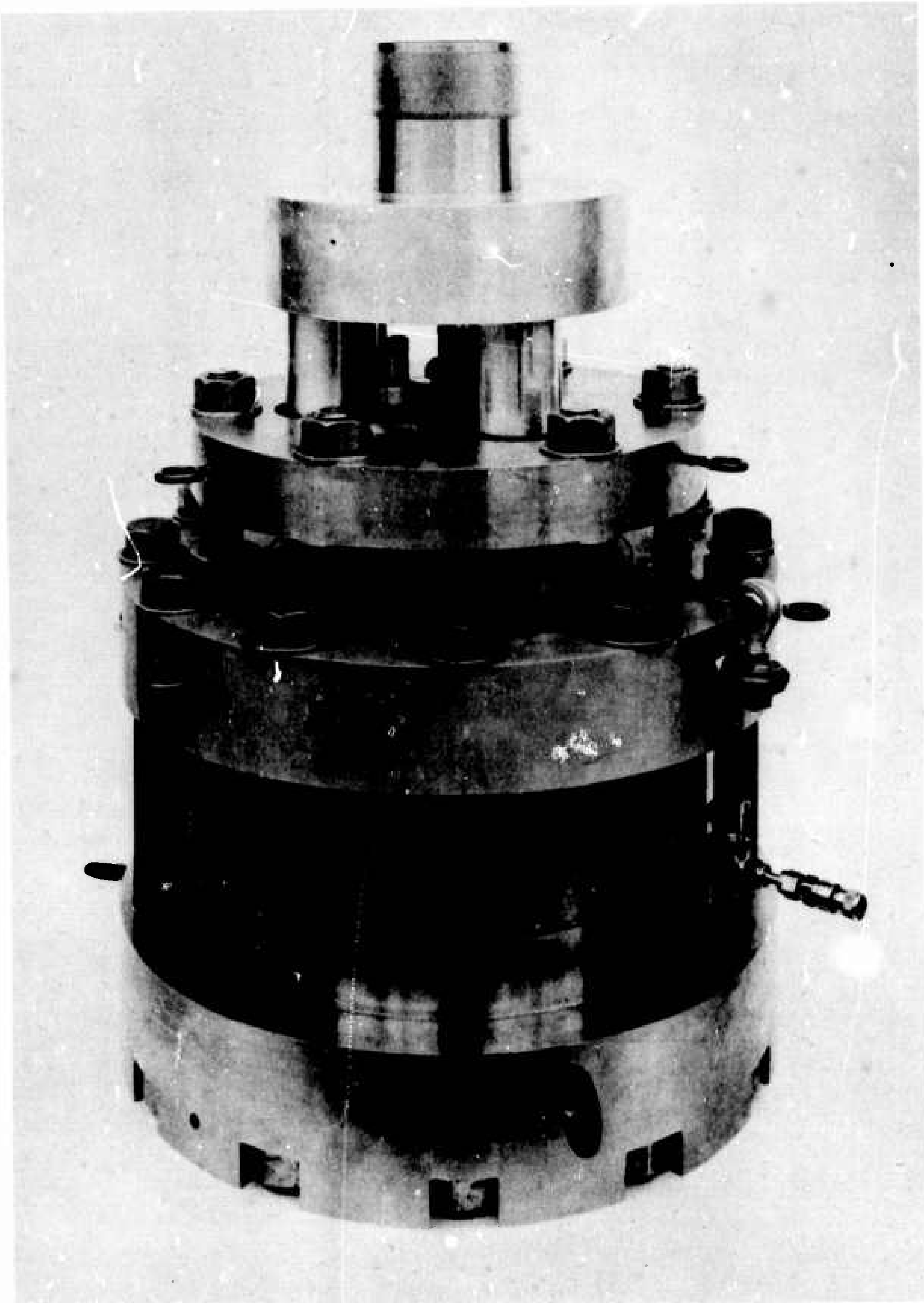


Fig. 16. Photograph of basic assembly for modified principal configuration.

from the flat-based load column of the available dynamic loading machine (Fig. 21) to the fluid-filled chamber above the specimen. The function of the LVDT coil support plate and the LVDT coil support columns is to support the zero-reference portions of the LVDT-type displacement transducers; the significance of this support system is discussed in Section 3.6. The function of the LVDT core housings is discussed in Section 3.5.

The key feature of the principal configuration is the implementation of the combined piston-fluid loading technique, the advantages of which were discussed in Section 2.3. It was anticipated that with this new loading technique the general-purpose WES device would be characterized by greater versatility and better performance than had been possible with devices previously developed. Fortunately, the principal objection to the combined loading technique--the expense involved in obtaining a dynamic loading machine--was not a problem at WES, since one such machine, the Dynapak, was already available (Fig. 38) and another, a 100-kip loader, was on order.

In the course of the preliminary testing program to evaluate the performance of the equipment, it was found necessary to modify the above-described configuration slightly by combining the soil container and the lower assembly container plate into a single piece; the reason for the change is discussed in Section 4.4. A drawing and a photograph of the modified device (i.e., the device, as modified and assembled in the principal configuration) appear in Figs. 15 and 16, respectively.

3.2.2 Auxiliary Configuration

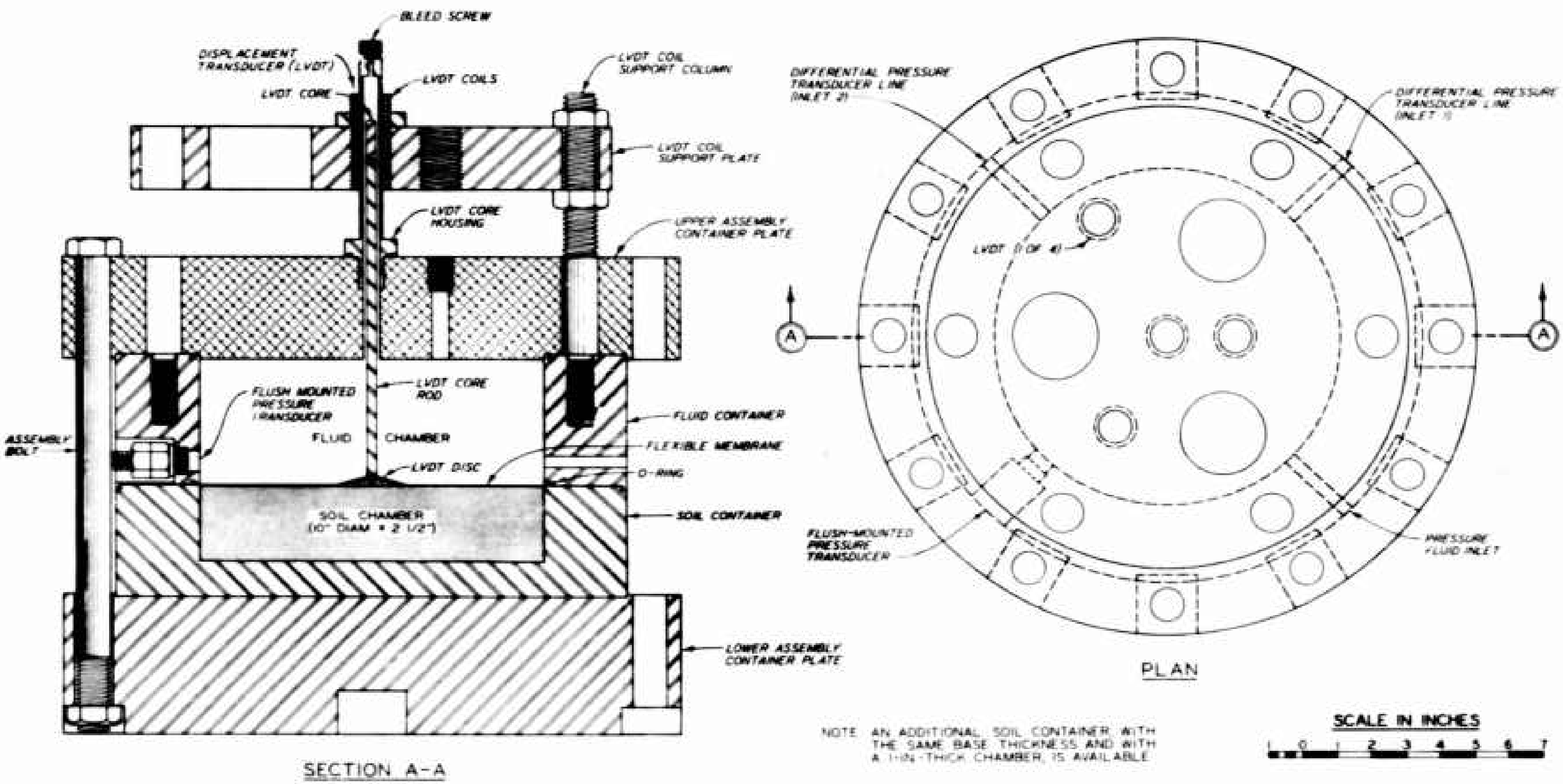
At the time of the design of the one-dimensional compression

device, both the Dynapak and the 100-kip loader were required for use on other projects, projects which had been used to justify and support their development. Since these loaders would be available for use with the one-dimensional compression device only on a part-time basis, it was thought to be desirable to provide an auxiliary system of load application which could be used when the dynamic loaders were not available. The auxiliary load-application system could be used for all tests for which accurate control of the loading characteristics would not be required--e.g., preliminary evaluation tests such as membrane leakage and transducer calibration, routine tests, tests on materials known to be rate insensitive, etc.--and thereby make it possible to expedite the one-dimensional-compression test program.

Unfortunately, there was no load generator available, or readily obtainable, which could provide the 80 kips required to develop 1000 psi in the fluid chamber of the device when assembled in the principal configuration. Consequently, it was necessary to design an auxiliary configuration for the equipment for use when the dynamic loaders were not available. A drawing depicting the original version of the auxiliary equipment configuration appears in Fig. 17.

When assembled in the original auxiliary configuration, the one-dimensional compression device consists of a soil container, a fluid container, a pair of assembly container plates, a support structure for the zero-reference portions of the displacement transducers (LVDT's), and a set of LVDT core housings.

Since the fluid is not pressurized by means of a piston when the device is assembled in the auxiliary configuration, the device in this



WES 10-IN-DIAM ONE-DIMENSIONAL COMPRESSION DEVICE

Fig. 17. Drawing of basic assembly for original auxiliary configuration.

configuration does not differ significantly, except in size, from the fluid-loading devices described in Section 2.3. The upper assembly container plate, the only new piece required for this configuration, is a solid plate and serves as the upper boundary for the fluid chamber. The other elements shown in Fig. 17 and their major functions have already been described above in connection with the principal equipment configuration. Several methods of load application were investigated for use in conjunction with the auxiliary configuration, and the results are discussed in Section 3.4.

It should be noted that the various elements which comprise the specimen-containment system, the load-support system, and the measurement system are essentially the same, whether the device is assembled in the principal configuration or in the auxiliary configuration; only the elements in the load-application system are different. The reason for this is that the auxiliary configuration was not intended to represent an additional device, but rather a substitute load-application system for the same device. Consequently, those elements of the principal equipment configuration which were not included in the load-application system associated with that configuration (instrumentation as well as equipment) were incorporated into the auxiliary equipment configuration wherever possible.

In the course of the preliminary testing program to evaluate the performance of the equipment, the auxiliary configuration was found to have certain undesirable characteristics not present in the principal configuration. This was corrected by making the auxiliary configuration more like the principal configuration, as shown in Fig. 18. The only new components required for the modified configuration were the six reaction-frame

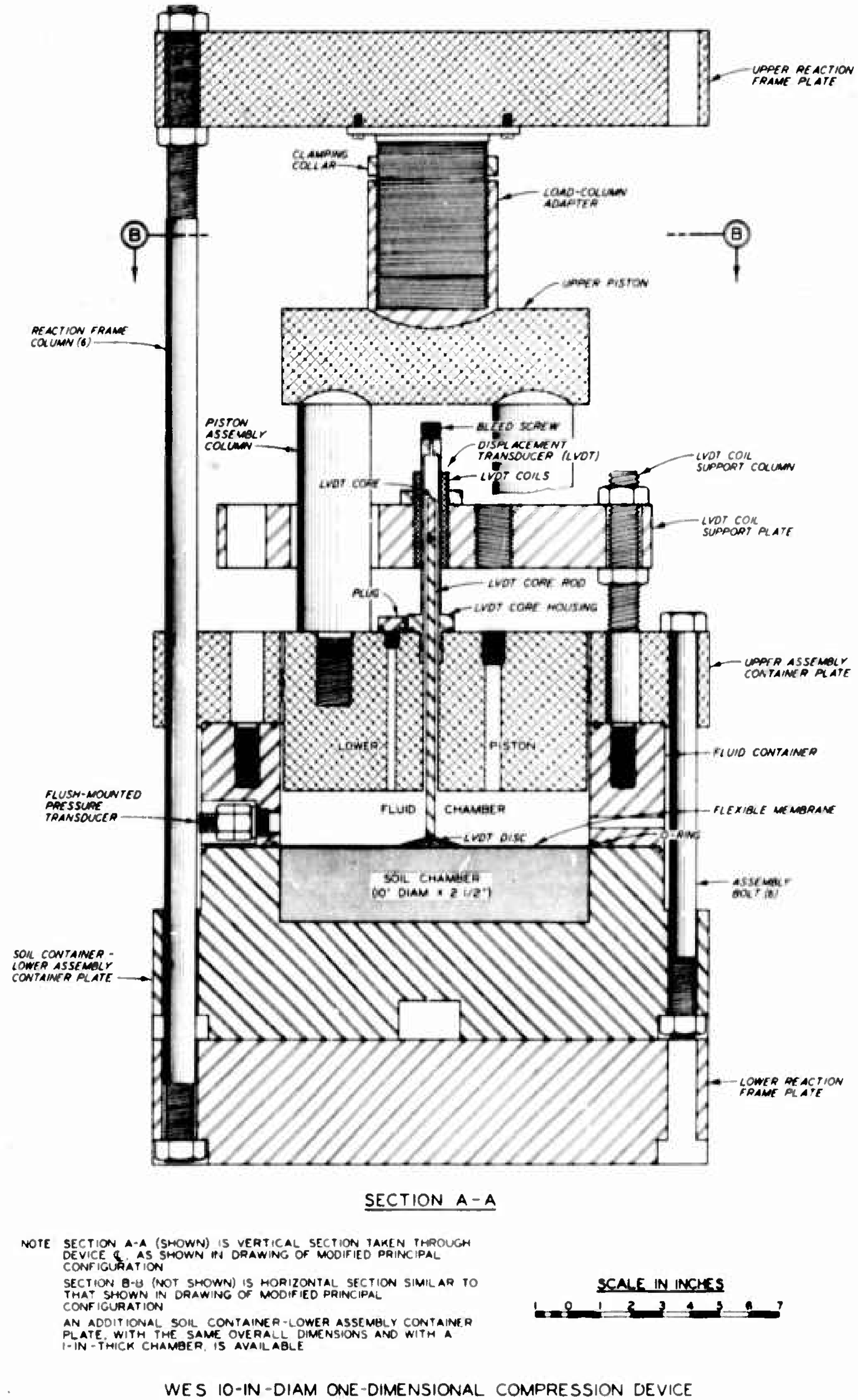


Fig. 18. Drawing of basic assembly for modified auxiliary configuration.

columns and the single reaction-frame load column; the solid-plate upper assembly container plate was adapted for use as the upper reaction-frame plate, and the old lower assembly container plate (which was no longer needed when the single-piece soil container-lower assembly container plate replaced it) was adapted for use as the lower reaction-frame plate. The reason for the change and the benefits which were realized are discussed in Section 4.4.

3.2.3 Summary

Two equipment configurations were selected for use with the one-dimensional compression device. It was anticipated that the principal configuration, which requires the use of a dynamic loading machine to generate the load on the specimen, would be used whenever control of the characteristics of the applied loading would be an important consideration; otherwise, the auxiliary configuration would be used. It was thought that this procedure would make it possible for the Dynapak loader and the 100-kip loader to be used in other test programs without significantly delaying the one-dimensional compression test program. Drawings depicting the two equipment configurations appear in Figs. 14 and 17.

The preliminary testing program for equipment evaluation uncovered certain difficulties associated with each of the two original equipment configurations, and both were then modified so that improved performance could be obtained. Drawings depicting the two modified equipment configurations appear in Figs. 15 and 18.

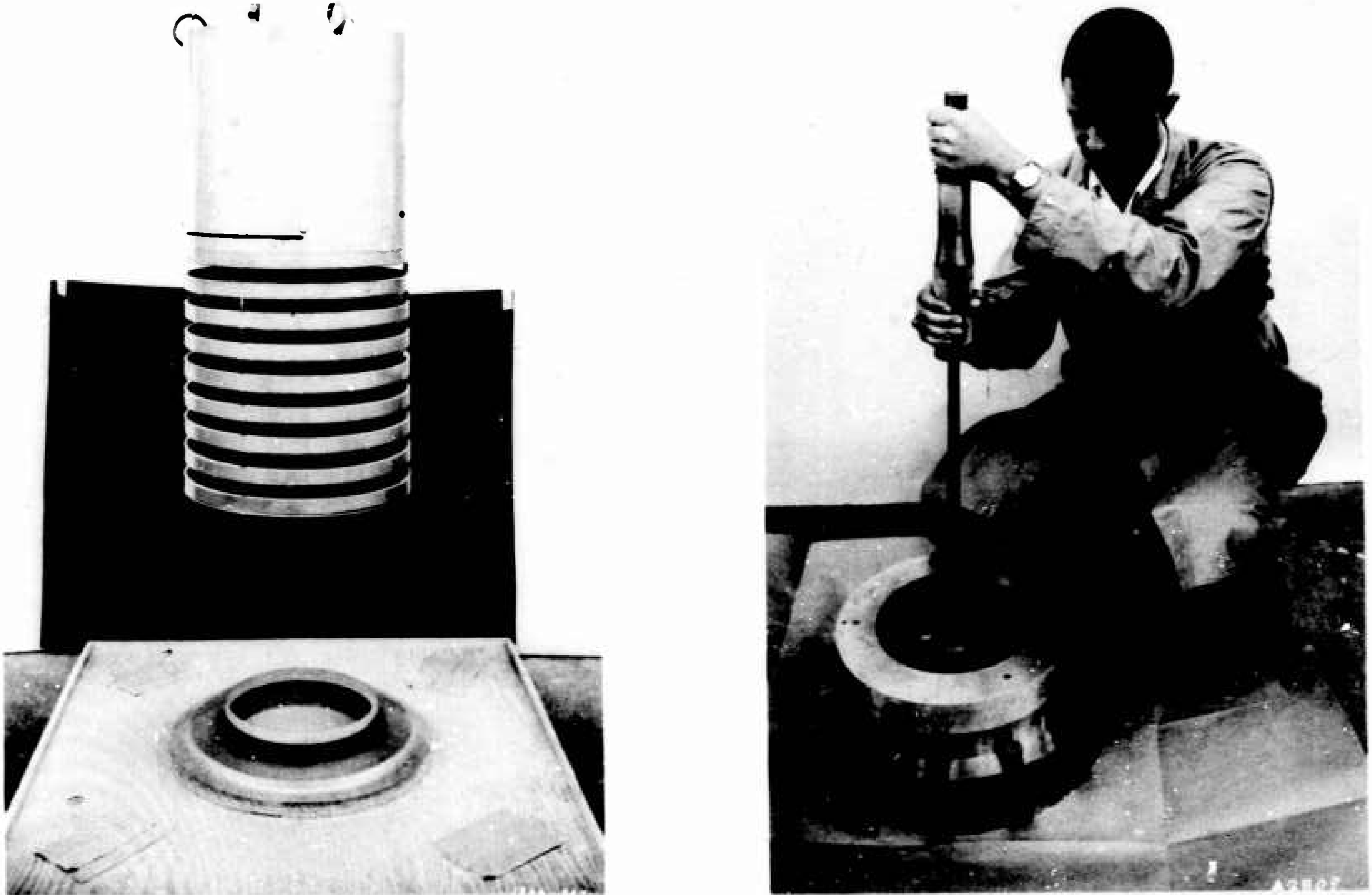
3.3 Specimen-Containment System

3.3.1 Type of Specimen-Containment System

A single-piece soil container, similar to those used at MIT, SRI, and CERF (see Section 2.3), was selected as the specimen-containment system for the WES device. Although basically very simple, the single-piece soil container permits a great deal of versatility in the nature and size of specimen which can be accommodated, making it well suited to any type of general-purpose one-dimensional compression device.

Prepared specimens of all soil types are placed directly into the soil chamber by any of the conventional placement techniques. Fig. 19a, for example, shows a dry sand specimen being prepared by "raining"; Fig. 19b shows a cohesive specimen being prepared by dynamic compaction.

In all cases, the soil specimen encounters a solid boundary which prevents the escape of both soil particles and moisture under load. Although sidewall friction may appear to be a problem, its effects are easily minimized, especially for a device such as the one considered herein, in which a fluid is used to apply load to the specimen. The specimen geometry is simply selected so that the diameter is large relative to the depth, and the transducer for the specimen-deformation measurement is located in the central portion of the specimen, where there is little or no effect of sidewall friction (see Section A.2). In fact, not only can sidewall-friction effects be minimized, they can even be evaluated. This is made possible by selecting a chamber diameter which is large in absolute magnitude--e.g., 8 in. or more--so that the deformation of the specimen can be measured at several distances from the wall and the results compared.



a. RAINING OF DRY SAND SPECIMEN

b. DYNAMIC COMPACTION OF COHESIVE SPECIMEN

Fig. 19. Placement of prepared specimens into one-dimensional compression device.

Undisturbed specimens (an expression commonly used to denote high-quality sampled specimens) are also readily accommodated by the single-piece soil container. An undisturbed tube specimen and the tube in which it is contained are cut to a length very nearly equal to the depth of the soil chamber. The tube is then machined, and the specimen is cut and trimmed to a length exactly equal to the chamber depth. After the specimen and tube have been placed in the center of the chamber, the volume between the tube and the wall of the chamber is filled either with compacted sand or with a rigid fluid such as oil or water. (When a rigid fluid is used, a membrane is placed at the lower outside periphery of the ring to prevent leakage of the fluid into the specimen pores.) An undisturbed tube specimen in position in the WES soil container is shown in Fig. 20.

An undisturbed block specimen is prepared by trimming it either into an insert ring, which fits exactly into the soil chamber, or into a smaller diameter ring, which is placed in the center of the chamber and then surrounded by either compacted sand or by a rigid fluid (and membrane).

Although the sampled specimen does not encounter a solid boundary, as does the prepared specimen, the tendency of soil particles and moisture to be squeezed out under the confining tube (or ring) is resisted by the same pressure that causes it, since the pressure fluid above the tube pushes and seals the tube against the base of the soil chamber. Additional resistance is provided by the pressurized constraining medium which surrounds the tube or ring. It was recognized that sidewall-friction effects might be somewhat more of a problem for undisturbed specimens than for prepared specimens, depending on the extent of the effect (see Section A.2) and the size of the undisturbed specimen. It was thought that the

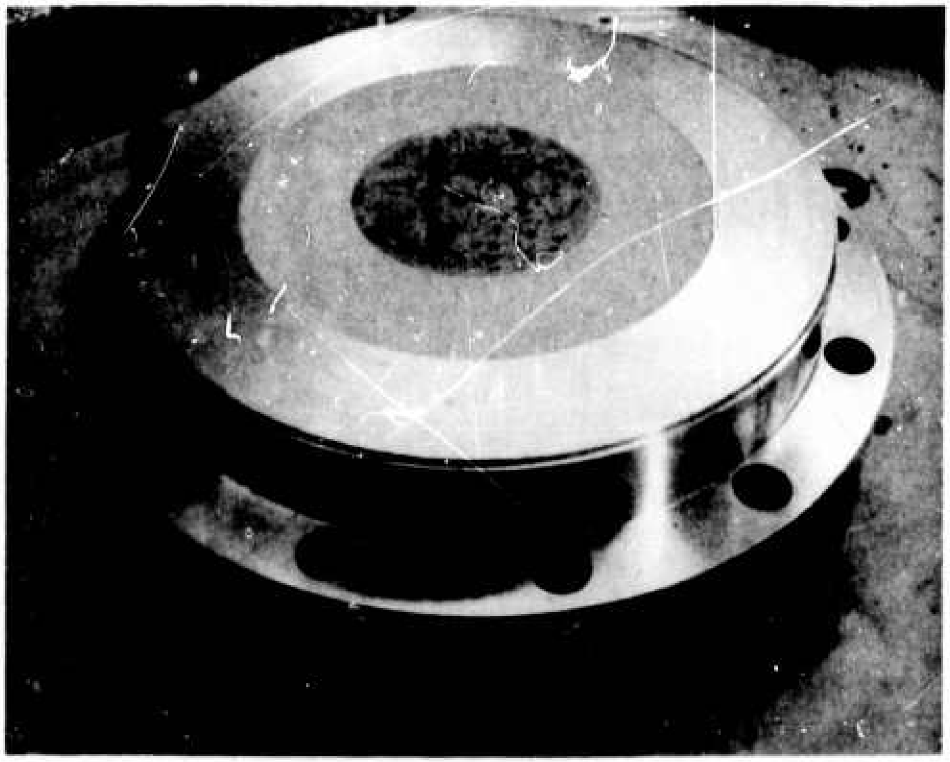


Fig. 20. Undisturbed specimen in position in one-dimensional compression device.

extent of the effect would be determined experimentally, as suggested above. In any case, it was anticipated that large undisturbed specimens would be used whenever possible to minimize the effects of sidewall friction and end disturbance.

3.3.2 Design Details

The selection of a specific type of soil-containment system was only the first step in its design. Dimensions were then selected for the specimen chamber so that (1) effects of sidewall friction, base friction, and end disturbance would be minimized, and (2) the specification concerning maximum pressure capability would be met. Thicknesses for the various soil-chamber boundaries were also established.

Diameter of the Specimen Chamber. In order to obtain a peak pressure of 1000 psi with the 100-kip loader, it was necessary to limit the specimen area to 100 sq in. and its diameter to approximately 10 or 11 in. A diameter of 10 in., exactly two and one-half times larger than the 4 in. in common use elsewhere, was actually selected. It was anticipated that, with a specimen this large, it would be possible to provide several displacement transducers at different distances from the center of the specimen, so that information concerning the effects of sidewall friction could be obtained.

Depth of the Specimen Chamber. A chamber depth of 2-1/2 in. was selected, so that the diameter-to-depth ratio for the specimen would correspond to the 4-to-1 ratio in common use. Although there was reason to believe that a lower ratio--and, consequently, a greater depth--could be used for large, fluid-loaded specimens (see Section A.2), no attempt was

made to take advantage of this in the original design. It was anticipated that this could be done at a later time when more information concerning the effects of sidewall friction would be available.

A chamber depth of 1 in. was also thought to be desirable, since nearly all the available one-dimensional compression data had been obtained from results of tests conducted with 1-in. specimens. Consequently, it was decided that two soil containers would be required for the device, one with a soil chamber 10 in. in diameter and 2-1/2 in. deep and the other with a soil chamber 10 in. in diameter and 1 in. deep.

<u>Thickness of the Lateral Boundary</u>. A one-dimensional compression test is by definition a test in which no strain is permitted in the specimen normal to the direction of applied loading. The principal function of the lateral boundary is to maintain this condition of no lateral strain by preventing the specimen from deforming laterally under load. Although it is not possible to prevent lateral deformations entirely in a short-duration test (see Sections 2.2 and A.3), the deformations can be kept small, so that the measured values of vertical strain are not significantly different from the values which would be obtained under conditions of absolute zero lateral strain. For the 10-in.-diam specimens in the WES device, it was anticipated that a 2-1/2-in.-thick steel boundary would be required to accomplish this (see Section A.3).

<u>Thickness of the Lower Boundary</u>. Since the principal function of the lower boundary is to transmit the load from the specimen to the next member in the support system, the design of this part of the soil-containment system is more appropriately considered in the discussion dealing with the load-support system (see Section 3.5).

3.3.3 Summary

The single-piece soil container was thought to be the best type of soil-containment system for a general-purpose device such as the one considered herein. Two soil containers were incorporated in the design, one with a specimen chamber 10 in. in diameter and 2-1/2 in. deep and the other with a specimen chamber 10 in. in diameter and 1 in. deep. It was anticipated that sidewall-friction effects would be evaluated by measuring the surface displacement of the specimen at several points on the surface.

In order to keep the lateral deformations of the soil specimens small, a 2-1/2-in.-thick lateral boundary was selected for the soil chamber. The thickness of the lower boundary is considered in the discussion dealing with the load-support system.

3.4 Load-Application System

3.4.1 Principal Configuration

The two load generators used in the principal configuration have already been mentioned (Section 3.2). The Dynapak, with an effective peak-load capability of 25 kips, was available and in use at the time the design of the one-dimensional compression device was undertaken. The other dynamic loading machine was on order at the time, and it was to have a peak-load capability of 100 kips. Since both loaders were required for use on other projects, no attempt was made to modify them to accommodate the one-dimensional compression device. Instead, the device was designed to be used with the loaders.

The transition configuration required to transfer load from the flat-based load columns of the dynamic loading machines to the fluid-filled

chamber above the specimen has already been described briefly (Section 3.2). Since the central part of the device had been preempted by the transducer for the key specimen-deformation measurement (see Section 3.6), a direct load transfer from the load-column adapter to the piston above the pressure fluid could not be used. The scheme selected (Fig. 15) not only freed the central part of the device for the key displacement transducer, but also freed enough of the remaining area to permit three additional displacement transducers to be located at the desired distances from the center (see Section 3.6).

In order to minimize the inertia of the load-application system, and thereby the resistance to short-duration loadings, it was decided to use aluminum for the upper and lower pistons and for the piston assembly columns. The possibility of galling of either the aluminum piston or the aluminum cylinder through which it moves (the upper assembly container plate) was minimized by specifying that both members be anodized.

Economy and convenience dictated the use of a readily available liquid for the pressure fluid. Ordinary tap water was selected.

Dynapak Loader. The specifications for this loader required the following control capabilities for a 10-kip load applied to a specimen with a spring constant of approximately 13 kips per in.:

(1) Rise Time: 3 to 150 msec

(2) Hold Time: 0 to 1000 msec

(3) Decay Time: 20 to 10,000 msec

WES personnel were satisfied that the Dynapak had met these specifications; in fact, it had been determined by experience that any desired hold time could be obtained.

A detailed discussion of the operation of the Dynapak loader is available (Cunny and Sloan, 1961); a schematic drawing of the loader appears in Fig. 21.

100-Kip Loader. The specifications for this loader required the following control capabilities for a 100-kip load applied to a specimen with a spring constant of 100 kip per in. (or less, if possible):

(1) Rise Time: 2 to 100 msec

(2) Hold Time: 0 to 1000 msec

(3) Decay Time: 2 to 1000 msec

The specifications also required that the actual load be within 5 percent and the time characteristics of the pulse within 10 percent of the values programmed for the test.

3.4.2 Auxiliary Configuration

The need for and selection of an auxiliary configuration have already been discussed (see Section 3.2). There were no requirements actually specified for the load-application system, other than its being capable of developing pressures up to 1000 psi in the fluid chamber. Consequently, the selection of the first system was based on considerations such as simplicity, safety, availability of components, ease of operation, and versatility.

Hydraulic System. Both simplicity and safety dictated the use of an hydraulic system and a liquid in preference to a pneumatic system and a gas; hydraulic systems are easier to seal at high pressures than are pneumatic systems, and they are far less likely to cause serious damage or injury in case of failure. It was decided to generate the pressures

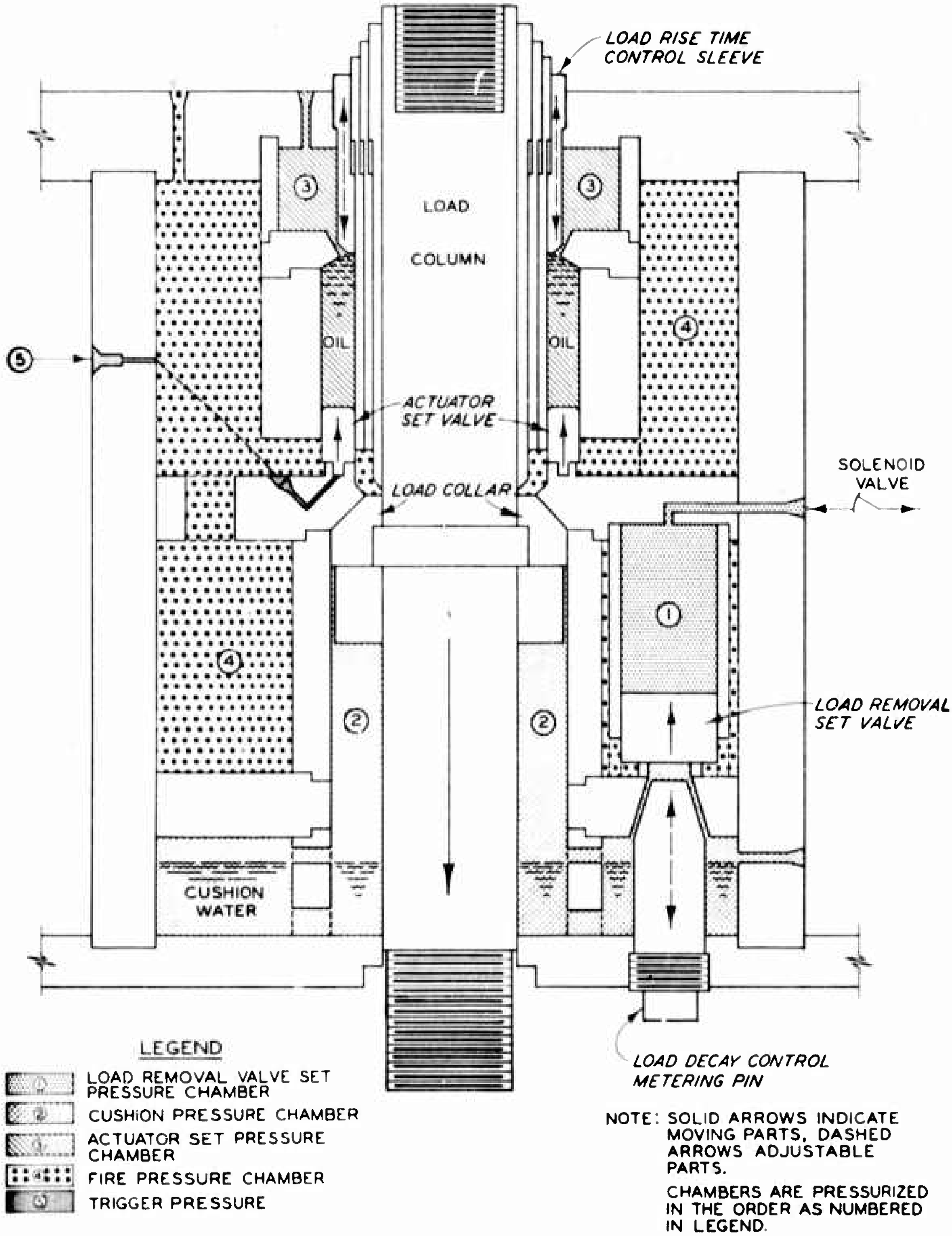


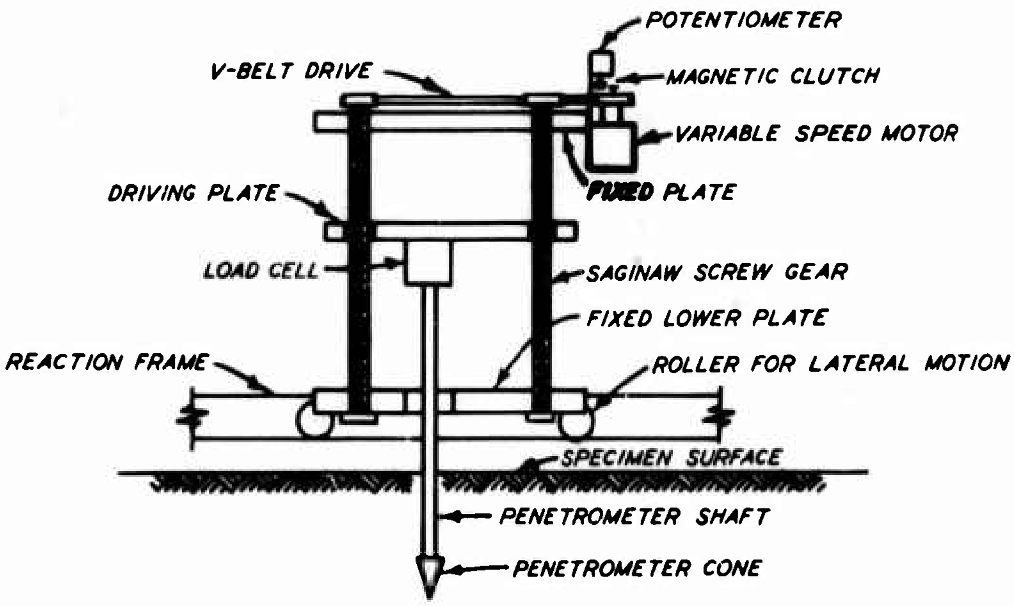
Fig. 21. Schematic drawing of Dynapak loader (from Cunny and Sloan, 1961).

required by mechanically driving a piston into a cylinder filled with the pressure fluid. Of the various techniques used to generate pressure in a liquid, this was thought to be the one best suited to high-pressure applications.

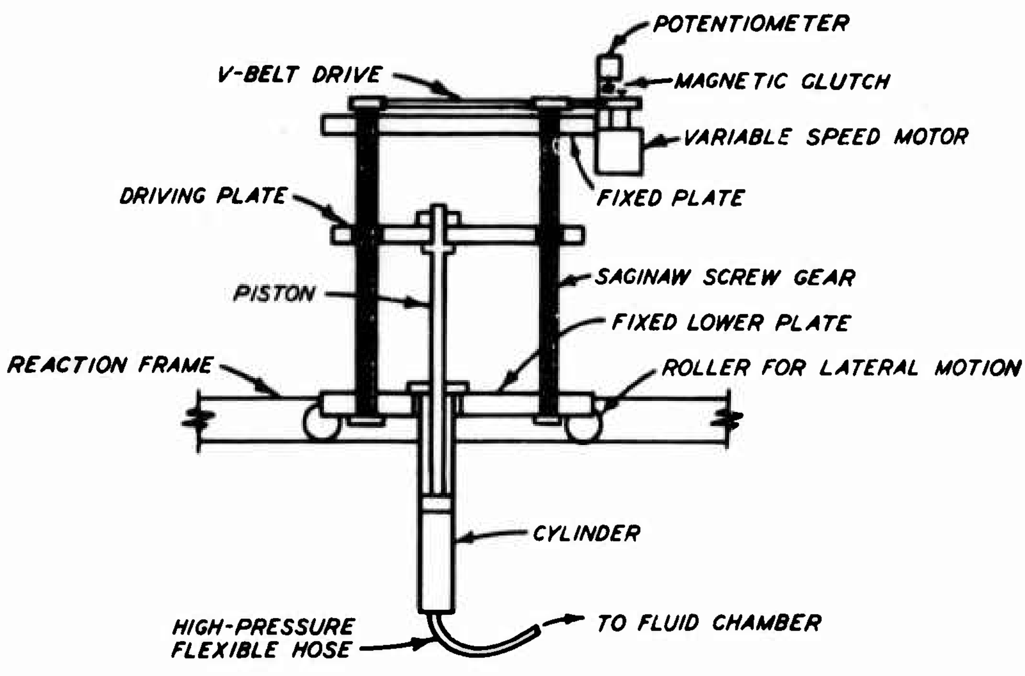
A mechanical system, which was being used as required to drive a cone penetrometer into large sand specimens (Fig. 22a), was adapted for use as the load generator (Fig. 22b). The remainder of the load-application system consisted of a piston, a cylinder, and a high-pressure flexible hose to connect the cylinder to the fluid chamber. When a series of tests was conducted to evaluate the performance of this hydraulic system, it was found to be unsatisfactory (see Section 4.3). The hydraulic system was then replaced by a simple pneumatic system.

Pneumatic System. The decision to change to pneumatic loading was based on several factors. Other types of gas-free hydraulic systems were not considered to be particularly well suited to high-pressure applications. Furthermore, the acquisition and installation of the necessary components for a new hydraulic system would have involved the investment of additional time and funds. A pneumatic load generator, on the other hand, was already available in the laboratory in the form of a series of commercially available pressurized nitrogen bottles. Pressures up to and exceeding those required could be obtained readily.

Initially, the pneumatic loading system consisted only of a nitrogen bottle (the load generator) and a high-pressure flexible hose (the transition configuration required to transfer pressure from the nitrogen bottle to the fluid chamber). As the preliminary testing program progressed, however, it was found to be desirable to add several components



a. DRIVING FORCE FOR CONE PENETROMETER



b. LOAD GENERATOR

A 1/12-HP, DC, GEAR MOTOR, WITH VARIABLE SPEED CONTROL (0 TO 86 RPM OUTPUT), DRIVES A GEARED OUTPUT SHAFT WHICH IS COUPLED ON FOUR CORNERS TO BELT-DRIVEN PULLEYS THAT TURN 1-IN SAGINAW SCREW SHAFTS TO LOWER (OR RAISE) A DRIVING PLATE WHICH RIDES ON BALL NUTS.

c. DESCRIPTION OF OPERATION

Fig. 22. Mechanical system in original and adapted applications.

to it. A Bourdon-type pressure gage was added so that the pressure in the line could be visually observed in the laboratory at all times. A pressure regulator and solenoid valve were added so that the application of load could be accomplished semiautomatically; the addition of another solenoid valve made the unloading process semiautomatic as well. Regulating valves were added to both the loading and unloading lines so that the rates of loading and unloading could be controlled. Finally, a pressure accumulator was added so that (1) a greater degree of control of the loading and unloading rates could be obtained, and (2) tests involving the use of the differential pressure transducer line could be conducted accurately (see Section 3.6).

Although the resulting pneumatic system was no longer simple (Fig. 23), it was versatile. In addition to serving as the load-application system for the auxiliary equipment configuration, the pneumatic system was used extensively in conjunction with the principal configuration. Simulated overburden pressures were applied by using the nitrogen to pressurize the water in the fluid chamber; tests involving the use of the differential pressure transducer line were made more accurate by using a large volume of pressurized nitrogen to stabilize the initial pressure, and many of the evaluation tests conducted with the equipment assembled in the principal configuration were expedited considerably by using the pneumatic load-application system to pressurize the fluid chamber.

Although the performance of the pneumatic load-application system was found to be quite satisfactory at first, it was later found that the use of nitrogen in the fluid chamber was incompatible with the use of the LVDT displacement transducer (see Section 4.3). Fortunately, it was

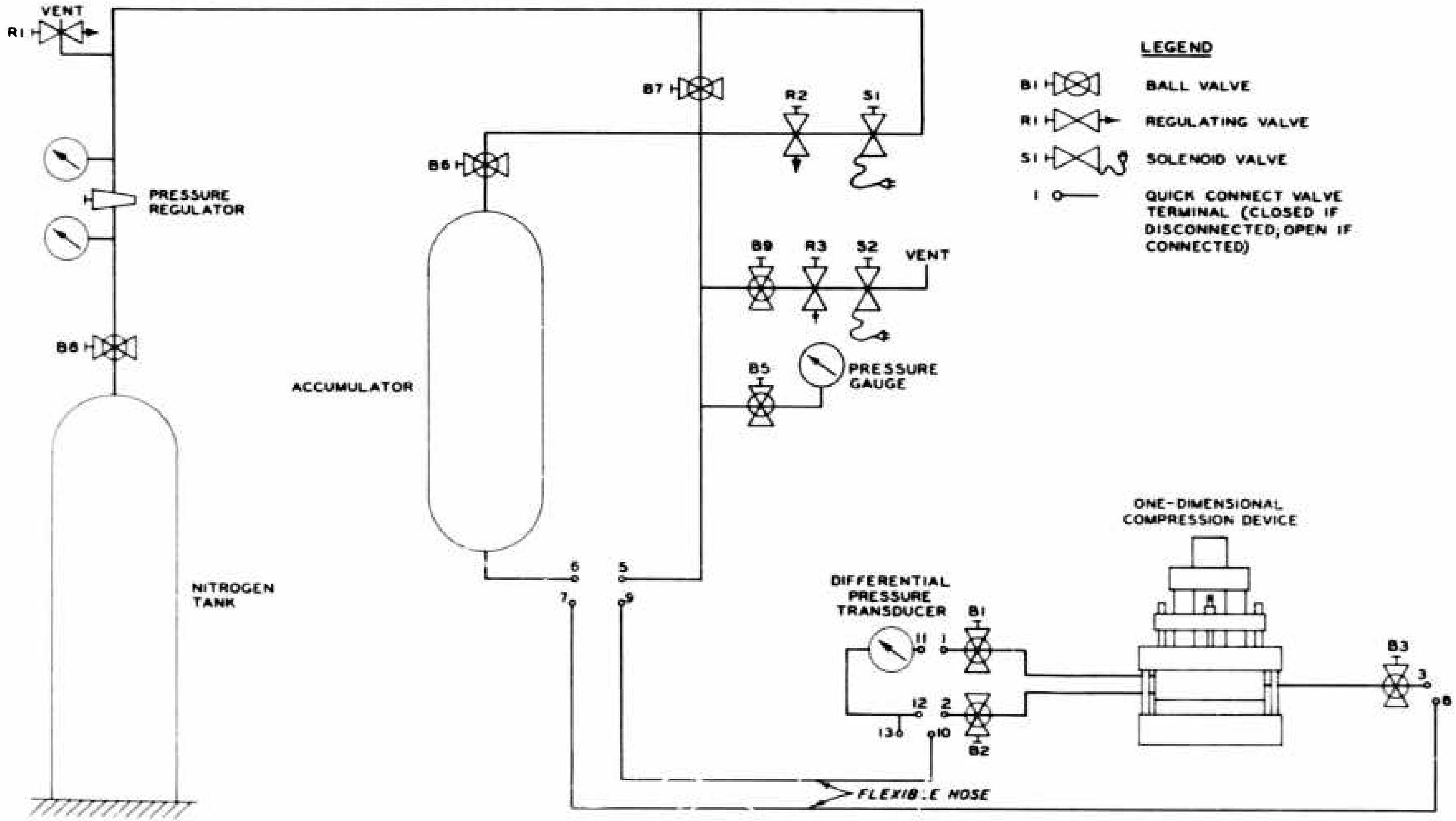


Fig. 23. Schematic drawing of pneumatic system.

possible to correct the difficulty by making a small modification to the load-application system. The fluid chamber was filled with water so that there would be no gas in the fluid chamber to affect the displacement measurement, and the rest of the pneumatic system was retained without modification.

Pneumatic-Hydraulic System. The resulting pneumatic-hydraulic system, in which a compressed gas is used to pressurize a liquid in the fluid chamber, is very similar to those used at MIT and CERF (Section 2.3). Consequently, it was anticipated that it would be possible to conduct fairly short-duration tests with the equipment in the auxiliary configuration in addition to the long-duration tests originally anticipated. In general, the operation of this load-application system proved to be quite satisfactory. One difficulty which was encountered, that of mixing of the nitrogen with the water under pressure, was corrected by inserting a barrier chamber in the line (see Section 4.3).

A schematic drawing of the final pneumatic-hydraulic load-application system is shown in Fig. 24.

3.4.3 Summary

The two dynamic loading machines used as load generators in conjunction with the principal equipment configuration of the one-dimensional compression device were designed for use in other projects. Rather than modify these loaders in any way, it was decided to design the one-dimensional compression device to "fit" the loaders; this was accomplished by selecting an appropriate transition configuration from the load columns of the dynamic loading machines to the fluid-filled chamber above

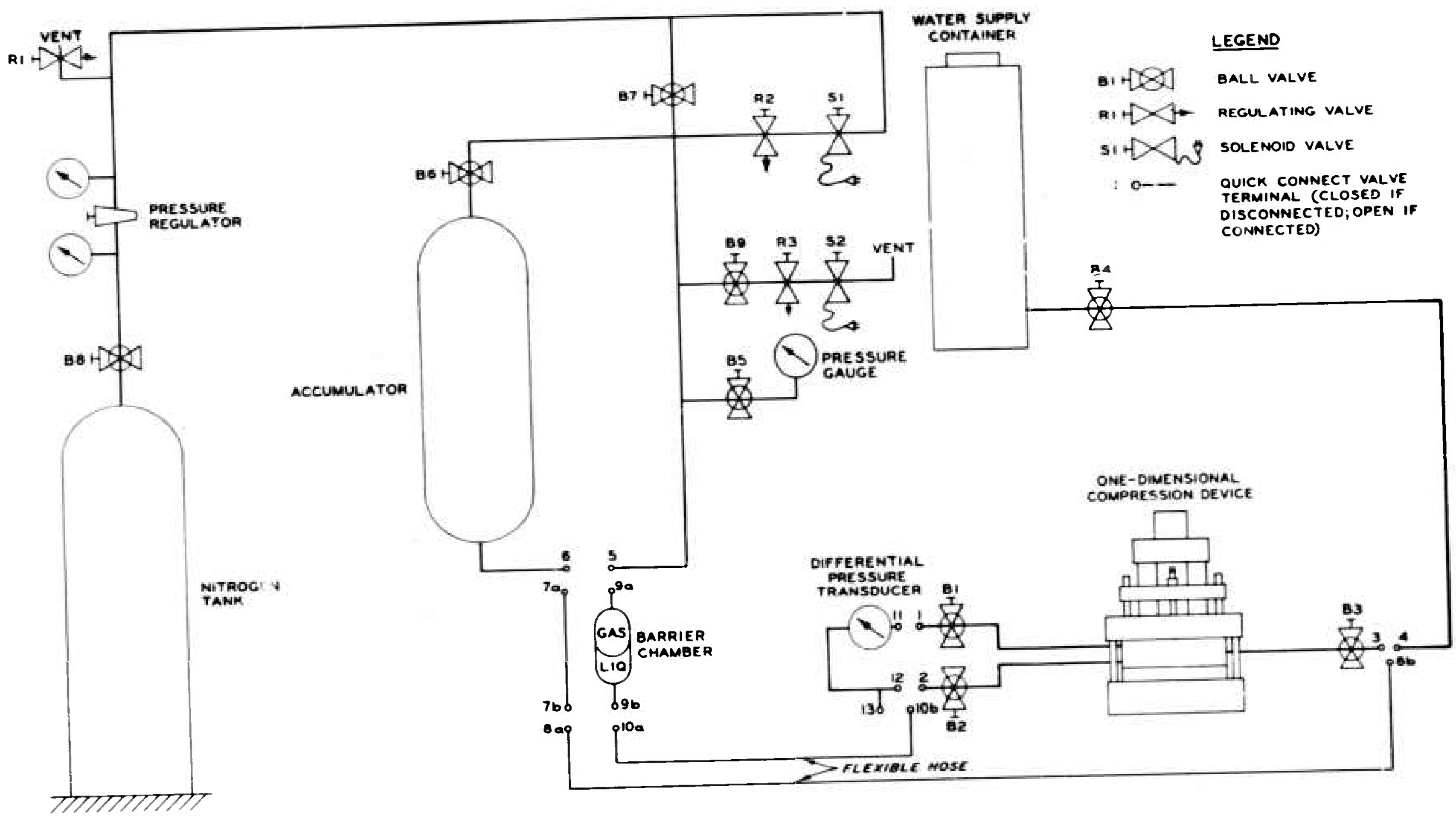


Fig. 24. Schematic drawing of combined pneumatic-hydraulic sys'em.

the specimen. Aluminum was used for the members in the load-application system, and ordinary tap water was selected for the pressure fluid.

Several methods of load application were considered for the auxiliary configuration, and several were actually used. After an hydraulic system and a pneumatic system had proven to be unsatisfactory, a combined pneumatic-hydraulic system (Fig. 24) was selected.

3.5 Load-Support System

3.5.1 Mechanical Support System for Nonvertical Loads

The nonvertical loads considered in the design of the load-support system include the radial pressure in the pressure fluid, the radial stress in the specimen, and the horizontal component of the applied load.

The radial pressure in the pressure fluid and the radial stress in the soil specimen are supported by the ring action of the fluid container and the soil container, respectively. The design of the soil-container ring, as discussed above (Section 3.3), was based on the no-lateral-strain requirement of the one-dimensional compression test. A 2-1/2-in.-thick ring was thought to be required. The same thickness was then arbitrarily selected for the fluid-container ring.

Since it is not possible to keep the axis of the Dynapak load column absolutely vertical, there is generally a small horizontal component in the applied loading. It is probably small enough to be neglected. Nevertheless, in the interest of safety--and, also, for convenience in assembly--shear connections were provided between all members.

3.5.2 Mechanical Support System for Vertical Loads

The vertical loads considered in the design of the load-support system include the applied load and the induced load. The applied load refers to the vertical force (or pressure) in the fluid chamber (and in the soil specimen). The induced load refers to the vertical force (or pressure) which acts at the fluid container-soil container interface to separate the two members; it is caused by intrusion of the pressure fluid up to the O-ring at the interface.

Nature of the Support System. It was recognized that in order to prevent the induced load during a test conducted in either of the two equipment configurations from forcing the fluid container off the soil container, it would be necessary to connect the two members. A direct bolted connection through the walls of the two members, similar to that used in the MIT test facility (Fig. 7), was considered to be undesirable, and an indirect connection--a reaction frame, consisting of a ring-type upper assembly container plate, a solid lower assembly container plate, and a set of assembly bolts (Fig. 14)--was selected instead. (The undesirable consequences of a direct connection include specimen disturbance during torquing of the bolts, the effect of the large holes in the soil-container wall on lateral constraint and on lateral-stress measurement, the effort required to keep the holes clean during specimen preparation, the effect of damage to the threads inside any of the holes, and the need for thick-based and hence massive soil containers.)

In addition to preventing the fluid container from being separated from the soil container during a test, the support system selected for the induced load also provided a mechanism for clamping the fluid

container to the soil container prior to a test. Clamping the two containers together before a test compresses the O-ring at their interface and seals the pressure chamber. It also makes it possible to reference the specimen-surface displacement measurement to the soil container without the need for any undesirable holes in that member (see Section 3.6).

In the auxiliary configuration, the support system selected for the induced load was readily extended to include the applied load by specifying that a solid, rather than ring-type, upper assembly container plate be used (Fig. 17). The solid upper assembly container plate provided not only a support mechanism for the applied load, but also an upper boundary to the fluid chamber. There was no need to provide a supporting mechanism for the applied load in the principal configuration, since the reaction frame of the load generator satisfies this requirement.

There was some consideration given to the advisability of combining the fluid container and upper assembly container plate into a single piece (upper member), and to combining the soil container and lower assembly container plate into another single piece (lower member). Both combinations were rejected, however, when it became apparent that four heavy and bulky combined pieces--one upper member for each configuration and one lower member for each soil container--were needed to replace the five uncombined pieces. (The fluid container, the lower assembly container plate, and the two soil containers were designed to be used in either of the two original equipment configurations.)

The decision not to combine the soil container and the lower assembly container plate into a single piece proved to be quite unfortunate. In the course of the preliminary testing program to evaluate the

performance of the equipment, considerable difficulty was encountered with equipment compressibility (see Section 4.4). The major source of difficulty, identified only after an exhaustive test series had been conducted, proved to be the interface between the soil container and the lower assembly container plate. At this point, the device was modified by combining the soil container and the lower assembly container plate into a single piece (Fig. 15). The equipment evaluation tests were then resumed. The results of these tests indicated that equipment compressibility was much less of a problem with the equipment assembled in the principal configuration than with the equipment assembled in the auxiliary configuration. Consequently, the load-support system in the auxiliary configuration was made more similar to that of the principal configuration. The reason for the modification and the advantages of the modified configuration are discussed in detail in Section 4.4.

Design Details. Once the nature of the support system had been established, dimensions were selected for the various members required.

The thickness of the solid upper assembly container plate and the size and number of assembly bolts were selected on the basis of strength requirements for the auxiliary configuration. A liberal factor of safety was applied in order to permit pressures exceeding 1000 psi to be used without fear of failure of any of the components. (Since strength was not the governing criterion in the design of any of the other members, the rest of the device was already overdesigned with regard to strength.) The ring-type upper assembly container plate, which also acts as the cylinder for the lower piston, was made thicker than required by strength considerations, so that some flexibility would be provided for the initial position

of the lower piston (prior to loading). Aluminum was used for both upper assembly container plates, in order to minimize the overall weight of the device.

Since it had been decided to use separate pieces for the soil container and the lower assembly container plate (in the original design), a nominal base thickness of 1 in. was selected for each of the soil containers, and the responsibility for resisting bending--i.e., excessive equipment deformations--was assigned to the lower assembly container plate. Selection of a thickness for the lower assembly container plate was delayed until the design of all the other components of the device had been completed. After the dimensions of the other components had been selected, it was found that a thickness of 4 in. for the lower assembly container plate would permit the device, with either of the two soil containers, to fit under the Dynapak loader. (Although the vertical position of the crossbeam of the Dynapak loader can be adjusted, adjustments can be made only in increments of 7-7/8 in., as can be seen from the notches in the Dynapak support columns in Fig. 38.) A 4-in.-thick steel plate was analyzed for failure and excessive deformation due to bending (by considering, conservatively, uniform loading on a simply supported circular plate), and it was found to be acceptable.

3.5.3 Leak Control for Pressure and Pore Fluids

Leakage in the one-dimensional compression apparatus may originate from two sources, the device itself or the load-application system used in conjunction with the auxiliary equipment configuration. Leakage originating in the device is of two types, internal and external. Internal

leakage refers to leaks within the pressure chamber, from the fluid chamber to the soil chamber or vice versa, and external leakage refers to leaks from either the fluid chamber or the soil chamber to some point outside both.

External Leakage at Surfaces. External leakage from the soil chamber can occur only by radial flow through the soil container-fluid container interface. External leakage from the fluid chamber can occur by radial flow through this same interface, by radial flow through the fluid container-upper assembly container plate interface, and by vertical flow through the lower piston-upper assembly container plate interface. An O-ring was used to seal each of these paths.

External Leakage Through Holes. Since there are no holes in the soil container, there is no possibility of external leakage from the soil chamber by flow through holes. There are several holes in the various boundaries of the fluid chamber, however, and each of these requires a seal to prevent leakage of the pressure fluid.

There are four holes in the fluid-container wall, equally spaced at 90 degrees (Fig. 14). Three of these are for hydraulic purposes, and are terminated by tube fittings threaded into the fluid-container wall. (One of the three, which serves as an inlet for the pressure fluid, can be seen in Fig. 15.) Leakage through the threaded connection was prevented by an O-ring at the fitting-fluid container interface; leakage through the fitting itself is prevented by a ball valve. The fourth hole in the fluid-container wall is for the flush-mounted pressure transducer, and it is sealed by an O-ring (with a simulated groove--see discussion below) at the transducer-fluid container interface.

There are two types of holes through the upper boundary for the fluid chamber, one for the passage of the LVDT core rod and one for the passage of the piezoelectric pressure transducer cable. The seal for each of these holes proved to be an innovation, at least for one-dimensional compression devices, and each is described below.

The conflicting requirements at the point where the displacement sensor (the LVDT core system) passes out of the pressure chamber have been discussed in connection with fluid-loading devices (Section 2.3). If the passage point is not sealed, leakage occurs; if it is sealed, the motion of the sensor is somewhat undesirably restricted by the seal. The conflict was resolved by devising a scheme which permits the LVDT core to be in close physical proximity to the LVDT coils, even though the core is inside the pressure environment and the coils outside. With the core and coils in close physical proximity, the transducer requirements are satisfied; with the core inside the pressure environment, there is no need for a seal which might restrict the motion of the core rod. These conditions were made possible by the use of a very thin-walled cylinder, or core housing, to separate the core from the coils (Fig. 14). (The wall thickness of the core housing, which is made of Type 304 stainless steel, is 0.04 in.) The threaded connection between the core housing and the member which acts as the upper boundary for the fluid chamber was sealed by an O-ring at the member-core housing interface. An O-ring was also used to seal the bleed hole at the top of the core housing.

The hole in the lower piston through which the cable for the piezoelectric pressure transducer passes was sealed by a modified version of a conventional cable seal. The fitting which provides the seal

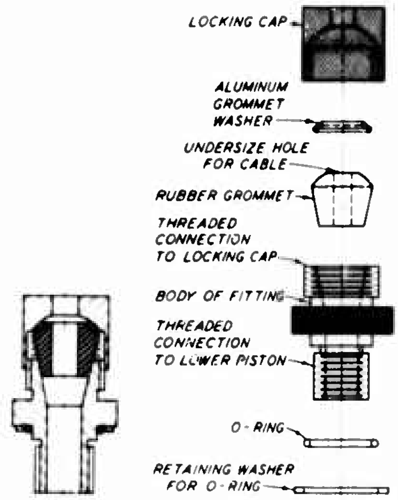
(Fig. 25) is threaded into either side of the member through which the cable passes (i.e., the type of cable seal shown can seal against a pressure in either direction through it); in the WES one-dimensional compression device, it is threaded into the top surface of the lower piston. The threaded connection was sealed by an O-ring at the lower piston-fitting interface. The cable itself was sealed by specifying that it pass through an undersize hole in a rubber grommet. Initially, the grommet is squeezed against the cable by tightening the cap; under pressure, this squeezing action and, hence, the sealing are intensified. Consequently, just as in an O-ring seal, the very pressure which tends to cause the leak is used to provide the seal for it.

A simple plug, in the form of a bolt with an O-ring seal, was provided for each of the holes in the device so that the device would be operational when one (or more) of the regular fittings was either not available or not required for a particular test.

Although most of the O-ring seals referred to above were of the conventional type, a simulated O-ring seal was used at several locations. The principle of the simulated seal is illustrated in Fig. 26 in connection with the seal for the bleed hole at the top of the core housing.

Internal Leakage. Freedom of flow between the fluid and soil chambers was prevented by using a flexible latex-rubber membrane to separate them. Various thicknesses of rubber were tried, and a thickness of approximately 0.030 in. proved to be best.

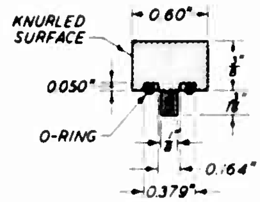
The membrane is continuous except for the point where the LVDT core system passes between the soil and fluid chambers. The seal originally designed for the passage point is shown in Fig. 27a. Although a



a. SECTION VIEW

b. EXPLODED VIEW

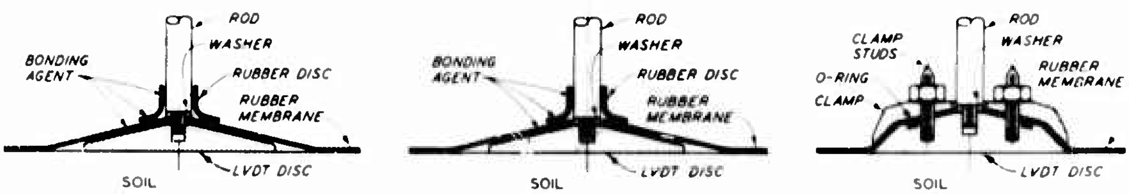
Fig. 25. Cable seal used for piezoelectric pressure transducer cable.



a. CONVENTIONAL SEAL

b. SIMULATED SEAL

Fig. 26. Simulated O-ring seal.



a. ORIGINAL BONDED SEAL

b. MODIFIED BONDED SEAL

c. O-RING SEAL

Fig. 27. Membrane seal for LVDT core system.

great deal of difficulty was encountered in finding a satisfactory bonding agent for the required application, one was eventually found (see Section 4.4). Performance of the seal was generally fair, and the occasional leaks which did occur were attributed to poor distribution of the bonding agent on the various surfaces. In the course of the preliminary testing program, it was found that the rubber clamped between the core-rod shoulder and the disc caused several problems in connection with the LVDT displacement measurement (see Section 4.4). When no other solution appeared to be available, that portion of the membrane was cut off, and the rod was shouldered directly on the disc (Fig. 27b). The results of subsequent tests indicated that the performance of the seal had not been adversely affected.

Because occasional leaks were encountered with the seals described above, and because a great deal of time was required for bonding each time a membrane had to be replaced, a new type of seal was designed. Although the new seal, shown in Fig. 27c, has not yet been used long enough to permit any definite conclusions to be drawn, there is every indication that its performance is superior to that of the seals previously used.

Pneumatic-Hydraulic System. Nearly all the pneumatic, hydraulic, and combined pneumatic-hydraulic lines that were selected for use in conjunction with the one-dimensional compression device were standard high-pressure tubing; standard high-pressure pipe and flexible hose were used in only a few locations. Wherever fittings and valves were needed, standard high-pressure equipment was used.

3.5.4 Summary

Load is transmitted to the pressure fluid above the soil

specimen by the various members in the load-application system. The lateral pressures generated in the fluid chamber are resisted by the fluid-container ring, and the lateral stresses generated in the soil specimen are resisted by the soil-container ring. Any tendency for lateral motion between members is resisted by lateral shear connections at all joints.

The load-support system selected for the applied and induced vertical loads in the pressure fluid consists of a pair of assembly container plates connected by a set of assembly bolts in each of the two equipment configurations (Figs. 14 and 17). In the principal configuration, the upper assembly container plate is a ring which surrounds the lower piston; in the auxiliary configuration, it is a solid plate which provides an upper boundary for the fluid chamber. The same lower assembly container plate and assembly bolts are used in the two configurations. In addition to preventing the induced load from forcing the fluid container off the soil container during a test, the support system also provides a reaction frame for the applied load when the equipment is assembled in the auxiliary configuration and a mechanism for clamping the fluid container to the soil container prior to a test. The preliminary testing program uncovered certain difficulties associated with the load-support system in each of the two original equipment configurations, and both were then modified so that improved performance could be obtained (Figs. 15 and 18).

In most cases, the types of seals selected for use in the WES device were the same as those which had been used with apparent success in other devices. There were several innovations, however. The most notable innovation was the use of a core housing with the LVDT displacement transducer to meet the conflicting requirements at the point where the

displacement sensor passes out of the pressure chamber, thereby resolving a problem of long standing (see Section 2.3).

3.6 Measurement System

3.6.1 Key Measurements

The first step in the design of the measurement system was to review the measurement systems used in other one-dimensional compression devices (Chapter 2), particularly the two key measurements from which the vertical stress and strain in the specimen are determined. In all the general-purpose test facilities (employing the multiple-reflection testing technique) which have been described above, the vertical stress and strain in the specimen were determined indirectly. In all the fluid-loading devices, the vertical stress in the specimen was determined by measuring the pressure in the fluid chamber, and the vertical strain in the specimen was determined by measuring the displacement of the specimen surface; in the piston-loading device, the vertical stress in the specimen was determined by measuring the force in the piston, and the vertical strain in the specimen was determined by measuring the displacement of the piston. All these techniques, and several others, were evaluated for use in the WES device. After a technique had been selected for each of the two measurements, the design was completed by selecting the type of transducer and the nature of the installation to be used for each.

The various design decisions were made on the basis of the following criteria:

(1) The relationship between the measurement made and the measurement desired (in the case of an indirect

measurement) should be such that it can be determined with an accuracy of 1 percent of the peak value of the measurement in any test.

(2) The accuracy of the measurement itself should be within 1 percent of the peak value of the measurement in any test.

(3) The type of electromechanical transducer selected should be such that the electrical output accurately portrays the mechanical input when the peak mechanical input is reached in a time equal to or longer than several milliseconds (see Section A.1).

<u>Vertical Stress</u>. Determining the vertical stress in the specimen by measuring the pressure in the fluid chamber appeared to be the best method available. Direct measurement of the soil stress was rejected for reasons already discussed (see Section 2.2). Determining the vertical stress in the specimen by measuring the force in the piston was also rejected, since this would be both less convenient and less accurate than measuring the pressure in the fluid chamber. Since there did not appear to be a better method available for determining the vertical stress in the specimen, measurement of the pressure in the fluid chamber was the method selected.

The type of transducer used to measure the fluid pressure in each of the fluid-loading one-dimensional compression devices described above (Section 2.3) was a diaphragm-type, strain-gage pressure transducer. Since there had apparently been no difficulties encountered with it, it was decided to use the same type of pressure transducer in the WES device.

The obvious location for a transducer of this type is inside one of the boundaries of the fluid chamber, where it can be mounted in such a way that its sensitive face is flush with the boundary surface. The nature of the installation selected is shown in Fig. 14. By placing the transducer in the fluid-container wall rather than in the member which acts as the upper boundary for the fluid chamber, it was possible to prepare a single position for the transducer that could be used for all tests (i.e., with the equipment assembled in either of the two test configurations). The flush mount assured that there would be no time lags in the measurement resulting from travel time of the pressure signal to the vicinity of the transducer.

Although several models satisfying the stated specifications were found to be readily available, the model actually selected--Statham Instruments, Inc., Model PG285TC--had the greatest number of desirable features for the intended application.

(1) Each unit was specified by the manufacturer to be linear statically to ±1 percent of the full-scale output, with infinite resolution.

(2) Frequency response of the units in the ranges desired was satisfactory (see Section A.4).

(3) All units in the ranges desired were mechanically interchangeable so that only a single installation would be required.

(4) The overall dimensions of each unit were small enough so that it could be installed conveniently in the fluid-container wall.

(5) The construction of each unit was such that a modified O-ring seal (see Section 3.5) could be used to seal the unit.

A photograph of the Statham Model PG285TC pressure transducer--an unbonded strain-gage transducer of the diaphragm type--is shown in Fig. 28.

<u>Vertical Strain</u>. Determining the vertical strain in the specimen by measuring the displacement of the specimen surface appeared to be the best method available for the configuration of the WES device. The only other reasonable possibility, measuring the soil strain directly, was rejected for reasons already discussed (see Section 2.2). (The presence of a fluid between the piston and the specimen prohibited the use of a piston-displacement measurement similar to that used in the UI device.) The problem of equipment compressibility, which arises when a surface-displacement measurement is used to determine specimen strain (see Section 2.2), was recognized. It was thought, however, that errors resulting from equipment compressibility could be held within tolerable limits (see Section A.5) by (1) proper selection of a location for the reference point relative to which the displacement would be made and (2) proper design of the load-support system. Consequently, it was decided to use a surface-displacement type of measurement.

The most convenient location for the reference point for the displacement measurement was considered to be some point fixed in space (i.e., physically removed from the vicinity of the device). For the fixed reference, the equipment components which contribute to the equipment-compressibility error include the base of the soil container, the lower

assembly container plate, and--in the principal equipment configuration--the foundation system of the load generator (see Section 2.2). Since it was recognized that little or nothing could be done to modify the existing Dynapak foundation, a test was conducted to determine its load-deformation characteristics. When the results indicated that the compressibility of the Dynapak foundation was greater than could be tolerated, the fixed reference was rejected. It was recognized that the reference point would have to be located within the device so that the displacement measurement would be unaffected by the gross motions of the device as a whole. Since it was thought to be undesirable to have any holes in the soil container, the fluid container was selected as the location for the reference point. It was anticipated that, with the fluid container rigidly clamped to the soil container by the assembly bolts, there would probably be very little difference between the two locations in any case (see Section 3.5). To assure that there would be no tendency for the fluid container to lift off the soil container, and thereby cause the specimen-deformation measurement to be significantly in error, the inside diameter of the O-ring groove at the top of the fluid container was designed to be larger than the inside diameter of the O-ring groove at the bottom of the fluid container (so that there would be a net downward force on the fluid container at all times). For the fixed reference in the fluid container--or, effectively, in the soil container--the only contributing components are the base of the soil container and the lower assembly container plate. These members were designed in such a way that their compressibility would not exceed the amount which could be tolerated (see Section 3.5).

In two of the three fluid-loading one-dimensional compression

devices described above (Section 2.3), the displacement of the specimen surface was measured by a linear variable differential transformer (LVDT), an inductive type of electromechanical transducer; a linear potentiometer was used in the third device. As discussed above, there is a problem in all three devices which arises from the conflicting requirements at the point where the displacement sensor passes out of the pressure chamber. Since it was necessary to sacrifice some aspect of the overall performance of each device in order to resolve these conflicting requirements, an attempt was made to avoid the problem entirely in the WES device by selecting a different type of displacement transducer. Several types of displacement transducers were found to be feasible for the intended application--the capacitance type, the optical-electronic type, and the reflected-wave type; however, all were rejected because they could not be installed conveniently in the configuration selected for the device.

Once the choice of displacement transducers had been narrowed to the two types previously used, the advantages of each were considered in detail. When possible installations were being examined for the LVDT, it became apparent that the conflicting requirements previously mentioned could be resolved without the need for any sacrifice in overall performance. Furthermore, they could be resolved even when the LVDT type of displacement transducer was used. The method for accomplishing this, as described above in connection with the design of the leak-control system, simply involves the installation of a very thin-walled cylinder at the top surface of the member which acts as the upper boundary for the fluid chamber. The installation of such a cylinder extends the pressure environment above the pressure chamber, where the LVDT core and coils can be in

close proximity to each other. Since the core remains in the pressure environment, the core system need not be sealed, and the freedom of motion of the displacement sensor is unimpeded. The method described clearly requires the use of a displacement transducer, such as the LVDT, in which the sensor (the core in the LVDT) is mechanically uncoupled from the reference (the coils in the LVDT). Consequently, it was decided to use an LVDT type of transducer in the WES device to measure the displacement of the specimen surface.

The various requirements which have been set in connection with the installation of the LVDT displacement transducer can be summarized as follows:

(1) The displacement must be sensed in the vicinity of the center of the specimen.

(2) The displacement must be sensed at the specimen surface.

(3) The reference relative to which the displacement is made must be located in the fluid container.

(4) The core and coils must be in close physical proximity for the measurement to be made.

(5) The core must remain in the pressure environment.

(6) The coils must be kept out of the pressure environment.

Although several aspects of the LVDT installation have already been discussed, details of the complete installation selected to meet the various requirements summarized above have not yet been described. The nature of the installation selected appears in Fig. 14. Requirement (1) was easily satisfied. Requirement (4) was satisfied by placing both the core and the coils just above the member which serves as the upper boundary

for the fluid chamber. A core system--consisting of a core, core rod, and disc--was designed to satisfy requirement (2), and a coil support system--consisting of a coil support plate and a set of coil support columns--was designed to satisfy requirement (3). Requirements (5) and (6) were satisfied by installing an LVDT core housing, which extends the pressure environment to the vicinity selected for the location of the core.

Two of the design details related to the installation of the LVDT displacement transducer are of general interest. One pertains to the type of material used for the core rod. Although Plexiglas rods were used initially, they were soon replaced by stainless-steel rods. Plexiglas was specified in the original design primarily because there was some concern about the effect of a metallic rod on the performance of the inductive-type LVDT transducer; a nonmagnetic material such as Plexiglas was thought to be safe. The reduced mass of a Plexiglas core rod was another, though a lesser, consideration. The change to steel was brought about by the results of the preliminary testing program, which indicated that a stiff core rod would be required (see Section 4.4). The stainless-steel core rods finally selected (Type 304) proved to be satisfactory with regard to stiffness (see Section 4.4), LVDT performance (see Section 4.5), and inertia (see Section A.4).

The other design detail of general interest is the connection between the LVDT coils and the coil support plate. The two requirements for the connection were that (1) the connection be rigid, and (2) that a fine adjustment capability be incorporated so that the LVDT could be nulled easily prior to a test (or adjusted, as desired, during a test). The two apparently conflicting requirements were resolved by using a fine-threaded

connection (50 tpi) between the coils and the coil support plate and a clamping collar to lock the coils in the adjusted position (Fig. 14).

The particular model of LVDT used--Schaevitz Engineering Type XS-LB--was selected because it had all the features required.

(1) Each unit was specified by the manufacturer to be linear statically to $\pm 1/2$ percent of the full-scale output, with infinite resolution.

(2) Frequency response of the units was satisfactory, even with the steel core rod (see Section A.4).

(3) All units in the ranges desired were mechanically interchangeable, so that only a single installation would be required.

(4) The cost of each unit was relatively small, even though (a) the coils were provided with a magnetic shield and a fine thread, and (b) the inside diameter of the coils was large enough to permit the use of a core housing.

A photograph of the Schaevitz type SX-LB LVDT is shown in Fig. 28.

3.6.2 Other Measurements

In contrast to the two key measurements, which were considered to be necessary parts of the overall device and were designed as such, there were several other measurements which were considered to be desirable for the device, but not necessary for its operation. These other measurements are listed below:

(1) Lateral stress in the soil specimen.

(2) Displacement of the specimen surface at several locations.

(3) Differential pressure (i.e., difference between total pressure and initial overburden pressure).

(4) Pressure in the central portion of the fluid chamber.

(5) Relative displacement between the LVDT coils and the base of the soil container.

In each case, a technique was devised by which the measurement could be incorporated into the overall configuration of the device. A particular type of transducer was then selected to make the measurement. In general, the selection of an appropriate type of transducer was influenced, though not restricted, by the types of transducers already available at WES. The nature of the installation selected for a transducer was influenced by the type of modification (to the device) which would be required for that installation; only when it was clear that each modification required would not compromise the performance of either the component modified or the device as a whole, was the installation accepted.

Lateral Stress in the Specimen. A measurement to determine the lateral stress induced in a soil specimen is desirable in that it provides data concerning the behavior of the soil under the conditions of the test. Such data are useful both for research applications and for practical applications.

A measurement of this type can be sensed within the soil specimen, at the outside periphery of the soil specimen (in a manner similar to that used to measure the pressure in the fluid chamber), within the soil-container wall, or at the outside periphery of the soil container. A direct measurement of the lateral stress within the specimen was rejected

for reasons already discussed (see Section 2.2). It was considered to be undesirable to place a transducer either at the outside periphery of the soil specimen or within the soil container wall, since both would require a hole in the soil container; consequently, these locations were rejected as well. Since there were no objections to the use of a transducer at the outside periphery of the soil container, this location was selected.

The instrument best suited to this type of measurement is the bonded strain-gage transducer. Although the measurement is indirect, in that the strain gage measures the circumferential strain at the outside periphery of the soil container, a relationship can be obtained between the radial stress on the wall of the soil chamber (i.e., the lateral stress in the specimen) and the circumferential strain measured by conducting a calibration test for this purpose. It was decided to install the strain-gage elements comprising the transducer on only one of the soil containers until the performance of the transducer could be evaluated, and the small soil container was arbitrarily chosen. The location selected for the strain-gage elements was 1/2 in. beneath the top surface of the soil container, corresponding to midheight of the soil chamber.

Two types of strain-gage elements were available at WES, and a pair of each type (one of each type for the measurement and one of each type for temperature compensation) was selected for use. The available elements were of the metal foil type--BLH Electronics FAB-25-12SX--and of the semiconductor type--Kulite-Bytrex DB-102. A photograph of both types is shown in Fig. 28.

Surface Displacements at Several Locations. The use of several displacement transducers at different radial distances from the center of

the specimen is desirable in that it provides a great deal of important information. In tests on carefully prepared, uniform specimens, the several transducers provide information on the effect of sidewall friction and the extent of the effect on specimens with various diameter-to-depth ratios. In tests on undisturbed specimens, they provide an indication of the statistical reliability which can be attributed to the data obtained.

It was decided that as many as four displacement transducers could be accommodated in the 10-in.-diam WES device. In addition to the transducer for the key measurement, which had already been designed to be located at the center of the specimen, three other transducers were designed to be located at radial distances of 2, 3, and 4 in. from the center (Fig. 14). The various design considerations (e.g., type of transducer, nature of installation) described above for the central LVDT (No. 0) are also applicable for each of the other three (Nos. 2, 3, and 4).

Differential Pressure. There are, in general, two separate applications of pressure in a one-dimensional compression test. The pressure first applied is generally applied slowly, either by pressurizing a pneumatic, hydraulic, or combined system or by jacking against a reaction frame; this initial pressure represents a simulated overburden pressure. (Even when the overburden pressure is zero, a small seating pressure is applied initially.) The next pressure applied, the pressure increment, is the actual test load. For tests in which the pressure increment to initial pressure ratio is small, it is difficult to obtain an accurate measurement of the pressure increment with the flush-mounted pressure transducer. The use of a differential pressure transducer in such tests is desirable in that it provides a measurement of the pressure increment alone.

(The corresponding displacement increment is readily obtained in the WES device by renulling and readjusting the gain of the LVDT displacement transducer after the initial pressure has been applied. This is made possible by the nature of the LVDT transducer and by the fact that the LVDT coils were kept out of the pressure environment and thereby accessible.)

Several differential pressure transducers were already available at WES in various ranges. Because the units were too large to be installed inside the device (see Fig. 28), an installation just outside the fluid chamber was arranged. (This remote installation prohibits the use of the differential pressure transducer for the very short-duration tests.) Two holes were provided through the fluid-container wall for the differential pressure transducer. A line leading from one of these holes is connected to one side of the transducer, and a line leading from the other hole is connected to the other side of the transducer. The valves of both lines are open as the initial pressure is applied, and no differential pressure occurs. However, before the actual test load is applied, the valve in one of the lines is closed. This provides a zero reference for the differential pressure. (The initial pressure is generally applied through the accumulator so that the pressure in the reference line can remain stable after the valve has been closed, even if there is a slow leak in the line.) When the load is applied, only this portion of the total pressure (i.e., the pressure increment) is sensed by the transducer. A schematic of the differential pressure transducer line is shown in Fig. 24.

The available differential pressure transducers were unbonded strain-gage pressure transducers of the diaphragm type--Statham

Instruments, Inc., Model PM280TC. A photograph of one of the units used is shown in Fig. 28.

Pressure Near Center of Fluid Chamber. The inclusion of a pressure transducer near the center of the fluid chamber, particularly one with high-frequency response characteristics, is desirable both for purposes of equipment evaluation and for general testing. A transducer of this type can be used to provide data necessary to verify the assumption of plane-wave loading. It can also be used to establish the presence or absence of high-frequency components during tests of very short duration. Furthermore, such a transducer can be used as a check or support measurement for the flush-mounted pressure transducer.

Several piezoelectric pressure transducers having excellent high-frequency response characteristics were already available at WES, and it was decided to use one of these in the one-dimensional compression device. Supported by a fitting at the top of the lower piston, the transducer hangs down into the central portion of the fluid chamber by its cable and measures the pressure in the fluid slightly above the surface of the specimen (Fig. 14).

The available piezoelectric pressure transducers had been fabricated at WES from commercially available tourmaline discs. A photograph of one of the units used is shown in Fig. 28.

Relative Displacement Between LVDT Coils and Soil Container. Although the ideal location for the LVDT coils is in the base of the soil container, practical considerations dictated the selection of another location (see discussion above). As a result, the displacement measurement used to determine the deformation of the soil specimen is in error by an

amount equal to the relative displacement between the LVDT coils and the base of the soil container.

The magnitude of this equipment-compressibility error can be predetermined for any given test by conducting a special calibration test in which either no specimen is used or a very rigid specimen such as steel is used. (With no specimen or with a very rigid specimen, the regular LVDT displacement transducer measures only deformations resulting from equipment compressibility.) If the particular test of interest is one in which the loading duration is very short, the calibration test should be conducted under the same conditions so that both the equipment deformations and the times at which they occur can be predetermined. The magnitude of the equipment-compressibility error can also be determined for a given test by measuring the relative displacement between the LVDT coils and the base of the soil container during the test. The advantage of the first method is that it does not require an additional channel of instrumentation; the advantage of the second method--principally for tests of short duration--is that it does not require an additional test for every test conducted. (The advantage does not apply for tests of long duration, since the first method requires only a single static compressibility determination, which is then applicable to all tests in which inertial forces are not great.)

It was originally anticipated that an equipment-compressibility determination would be made only once or twice in each configuration to verify the design assumption that errors resulting from equipment compressibility could be held within tolerable limits. The predetermination method was thought to be best for these few tests, and no provisions were made for an independent measurement. The tests were subsequently

conducted, and the results analyzed. It was clear from the results that the equipment compressibility in both configurations was too great to be neglected and that the displacement measurement used to determine the deformation of the specimen would have to be corrected for the deformations of the contributing equipment components (see Section A.5). In order to expedite the tests conducted with the equipment assembled in the principal configuration, it was decided to provide an independent measurement of the relative displacement between the LVDT coils and the base of the soil container for tests conducted in the principal configuration.

Since a direct measurement could not be used, it was decided instead to measure the accelerations of both the LVDT coils and the soil container. (The relative displacement between the two members can be determined by double integrating the two acceleration records obtained.) The accelerometer for the coils was located on the top surface of the coil support plate. The accelerometer for the soil container was located inside the base of the lower assembly container plate. It was anticipated that the absolute displacement of the lower assembly container plate would be very nearly equal to the absolute displacement of the base of the soil container at all times.

Several accelerometers were already available at WES in various ranges. Since the equipment accelerations could not be predicted accurately in advance, high-range units (50 g's) were selected for the first evaluation test. The results of this test were then used as a guide to the selection of proper range units for general use. Fortunately, the available accelerometers were mechanically interchangeable, so that they could all be used in the same installation.

The available accelerometers were of the unbonded strain-gage type--Statham Instruments, Inc., Model A69TC. A photograph of one of the units used is shown in Fig. 28.

3.6.3 Amplifiers and Recorders

The two key measurements used to determine the vertical stress and strain in the specimen in the WES one-dimensional compression device are made as a function of time. However, it is the relationship between the stress and the strain that is of primary interest. Since this relationship can be determined only by comparing the two key measurements at a series of specific times, it is important that the recorded data obtained be accurate in time as well as in amplitude. This can be assured by the selection of very high-frequency amplification and recording units, which afford excellent time resolution. It is also possible to use moderately high-frequency units (see below). If these units are properly selected, the phase shift or time error can be kept small; in any case, if the same amplification and recording units are used for both of the key measurements, the phase shift is probably very nearly the same for both measurements (since the cause-and-effect nature of the two measurements assures that they will have similar characteristics to begin with), and good time correlation can be obtained.

Recorder Types. It was anticipated that the frequency range of the various signals associated with the one-dimensional compression data would be 0 to 80 cps (see Section A.1). The recorders most commonly used in this frequency range--the light-beam oscillograph, the magnetic-tape unit, and the cathode-ray oscilloscope--were all considered for use with

the WES one-dimensional compression device, and the light-beam oscillograph was selected. The magnetic-tape unit was rejected because the data would not be immediately available for observation after a test. The cathode-ray oscilloscope was rejected because several units would be required for all the measurements made and because an accuracy of 1 percent would be very difficult to achieve in the data reduction. Although both the magnetic-tape unit and the cathode-ray oscilloscope have higher frequency-response characteristics than the light-beam oscillograph, it was anticipated that the frequency response which could be obtained with the light-beam oscillograph would be sufficient to meet the stated specifications for the one-dimensional compression device.

A dual-beam, cathode-ray oscilloscope was subsequently obtained as a supplementary recording unit, primarily to provide a capability for obtaining detailed time resolution on some portion of one (or two) of the measurements obtained during any given test. It was anticipated, for example, that the oscilloscope would be used in conjunction with the piezoelectric pressure transducer to examine any high-frequency pressure components that might be found. It was also anticipated that the oscilloscope would be used to verify the assumption that the frequency-response characteristics of the light-beam oscillograph are adequate for the loading durations of interest.

Amplifier Types. The use of the inductive-type LVDT displacement transducer to determine the deformation of the soil specimen made it necessary to select a carrier amplifier for this measurement. In order to provide the same type of amplification unit for both key measurements, a carrier amplifier was also selected for the flush-mounted pressure

transducer. In fact, it was possible to satisfy all but one of the amplification requirements in the measurement system with carrier amplifiers. A charge amplifier and--for use with the light-beam oscillograph--a galvanometer-driver amplifier were required for the piezoelectric pressure transducer.

Models Selected. The light-beam oscillograph and the two carrier amplifiers (each unit accommodates four instrumentation channels) used in conjunction with the one-dimensional compression device were already available at WES at the time the design of the device was undertaken. The characteristics of these units were evaluated, and it was anticipated that they would prove to be satisfactory for the required application. The available oscillograph was a direct-print unit--Consolidated Electrodynamics Corp. (CEC) Model 5-119--and the available amplifiers were 3-kc (carrier) units--CEC Model 1-118. The type of galvanometer selected for use was a Type 7-364.

Experience with similar units of the same types at WES had indicated that the limiting factor in the amplifier-recorder system with regard to frequency response was the galvanometer. Since this experience had been obtained with input frequencies from 0 to 500 cps, it was considered to be applicable to the one-dimensional compression data anticipated. The amplifier-recorder system selected was thought to have the following features:

(1) Static linearity to ±1 percent of the full-scale output of ±2-1/2 in. on the oscillogram (i.e., full excursion of 5 in.).

(2) Satisfactory frequency-response characteristics for the anticipated range of input frequencies.

(3) A well-matched galvanometer (current sensitivity of 0.4 milliamp per in.) and amplifier (±1.5 milliamp, at 25 percent of rated full-scale output) for optimum performance.

(4) A single recorder for all measurements, with the attendant simplification in synchronization during a test and in data reduction afterwards.

(5) A direct-print capability for recorded data, with the attendant benefit of being able to trace any problems observed to their source while the test setup is still in place.

(6) A satisfactory range of paper speeds for good time resolution for the anticipated range of input frequencies.

It should be pointed out that the static-linearity and the frequency-response features listed above were anticipated capabilities rather than manufacturers' specifications. The Type 7-364 galvanometer was actually specified by the manufacturer to be linear statically to ±3 percent of the full-scale output. However, experience at WES had shown that deviations of 3 percent occurred only when the amplifier was driven to its full capacity, and that the output was linear to ±1 percent of the peak value (or better) when the peak current was limited to approximately 25 percent of the rated full-scale output. Consequently, it was anticipated that a static-linearity capability of ±1 percent could be obtained. With regard to the frequency-response feature, there was no specification available for the particular

amplifier-galvanometer system selected. However, it was anticipated--on the basis of previous experience at WES, which had indicated that the galvanometer was the limiting factor--that the frequency-response characteristics of the entire system would be satisfactory (see Section A.4).

Charge-amplifier units and galvanometer-driver-amplifier units required for use in conjunction with the piezoelectric pressure transducer were already available at WES. One charge amplifier--Kistler Model 565S6--and one galvanometer-driver amplifier--Dana Model 2200--were selected. The particular model dual-beam, cathode-ray oscilloscope selected--Tektronix, Inc., Model 502A (equipped with Polaroid camera)--was a model frequently used at WES, and was readily available commercially.

A photograph of the instrumentation room which contains the various amplifiers and recorders used is shown in Fig. 29.

3.6.4 <u>Summary</u>

The measurement system designed for use in conjunction with the WES one-dimensional compression device is shown schematically in Fig. 30 (as is the electronic control apparatus for the Dynapak loader and for data synchronization). A photograph of the various electromechanical transducers selected is shown in Fig. 28, and a photograph of the instrumentation room where the measurements are amplified and recorded (and where the electronic control apparatus for the dynamic loader is located) is shown in Fig. 29. Each of the individual measurements is recorded as a function of time on the light-beam oscillograph. When better time resolution is required, it is possible to record any two of the measurements as a function of time on the dual-beam cathode-ray oscilloscope, and photograph the screen.

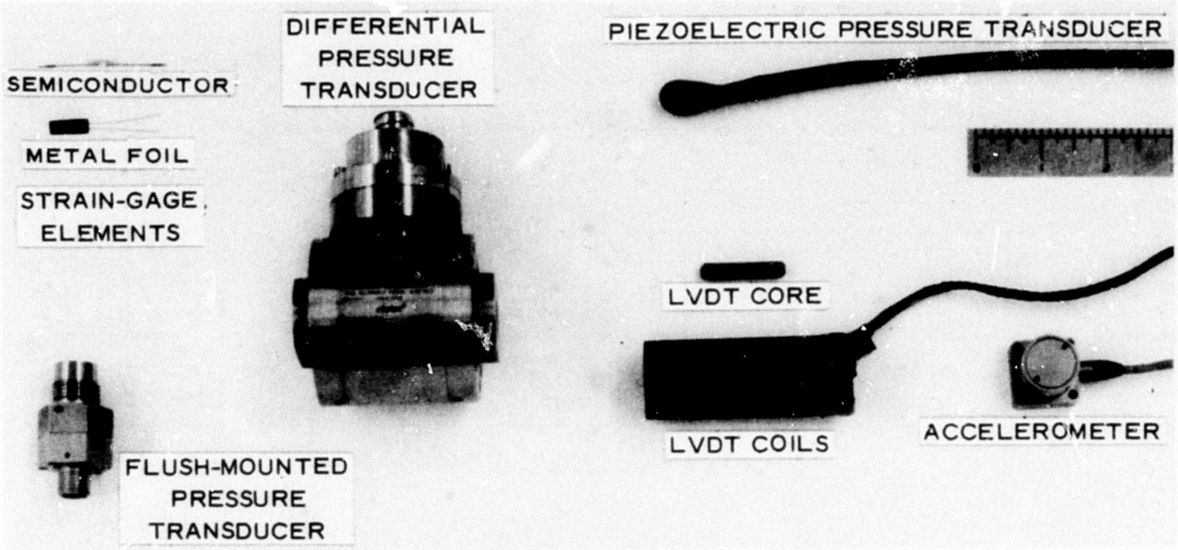


Fig. 28. Photograph of transducers selected for WES facility.

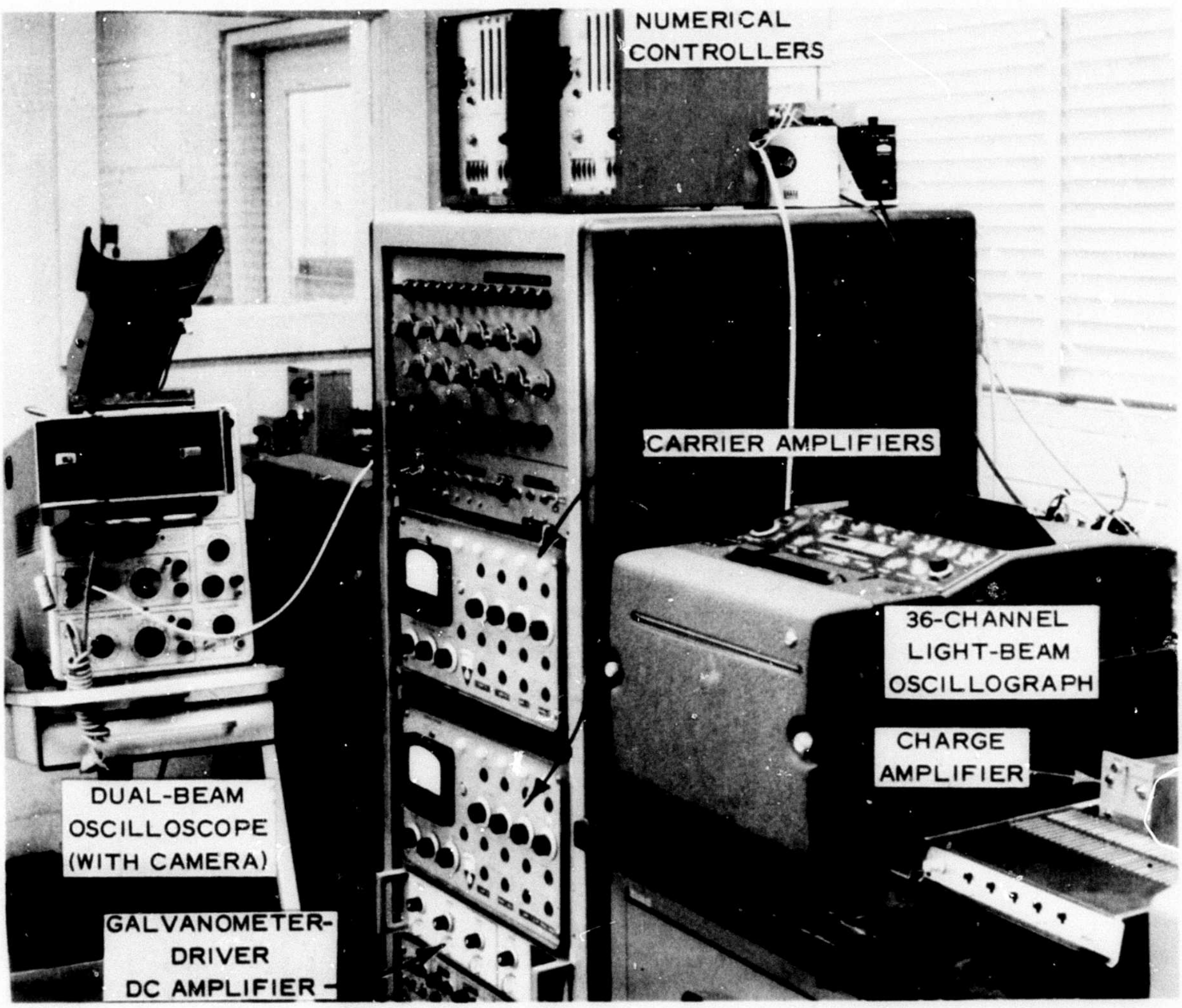


Fig. 29. Photograph of amplifiers and recorders selected for WES facility.

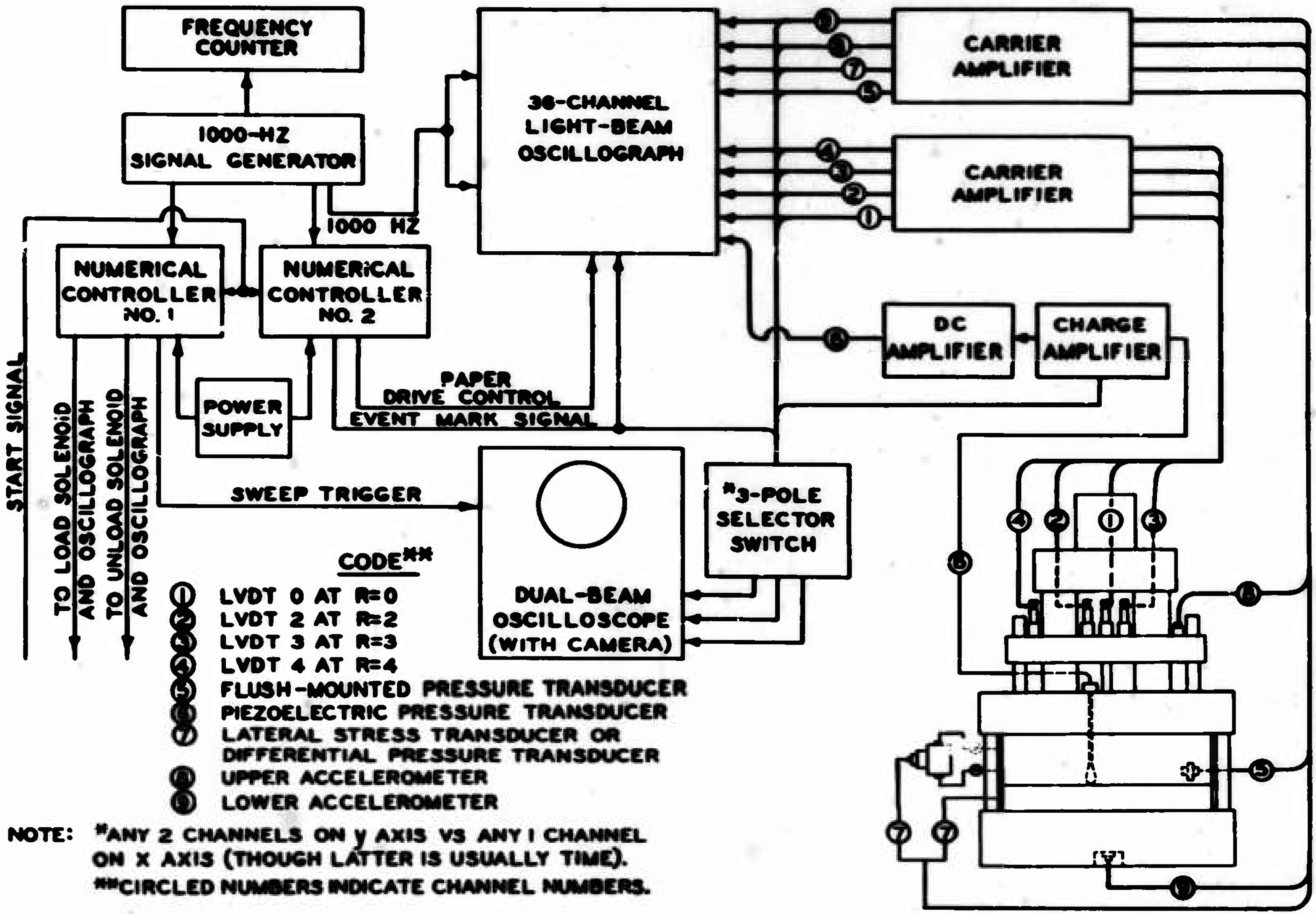


Fig. 30. Schematic drawing of measurement system designed for WES facility.

A diaphragm-type, strain-gage pressure transducer (Channel 5, Fig. 30) and an LVDT-type displacement transducer (Channel 1) were the transducers selected for the two key measurements (from which the vertical stress and strain in the specimen are determined). Locations selected for the two transducers were such that the vertical stress and strain in the specimen could be accurately determined from the measurements made. The pressure transducer was located in the fluid-container wall just above the specimen surface (Fig. 14). The sensor for the displacement transducer was located in the center of the device, and the reference for the displacement measurement was located in the fluid container (Fig. 14).

Other measurements were designed for use as desired. These include: (1) a measurement for the determination of the lateral stress in the soil specimen (Channel 7), (2) measurements for the determination of the specimen deformation at radial distances (R) of 2, 3, and 4 in. from the center of the device (Channels 2, 3, and 4), (3) a measurement of differential pressure (Channel 7), (4) a measurement of pressure with high-frequency response characteristics in the center of the specimen (Channel 6), and (5) a measurement for the determination of the relative displacement between the base of the soil container (Channel 9) and the coil support plate (Channel 8).

The transducers, amplifiers, and recorders selected for use in conjunction with the WES one-dimensional compression device are commercially available items, and their characteristics and principles of operation are described in the Shock and Vibration Handbook (Harris and Crede, 1961).

CHAPTER 4

EVALUATION OF THE TEST FACILITY

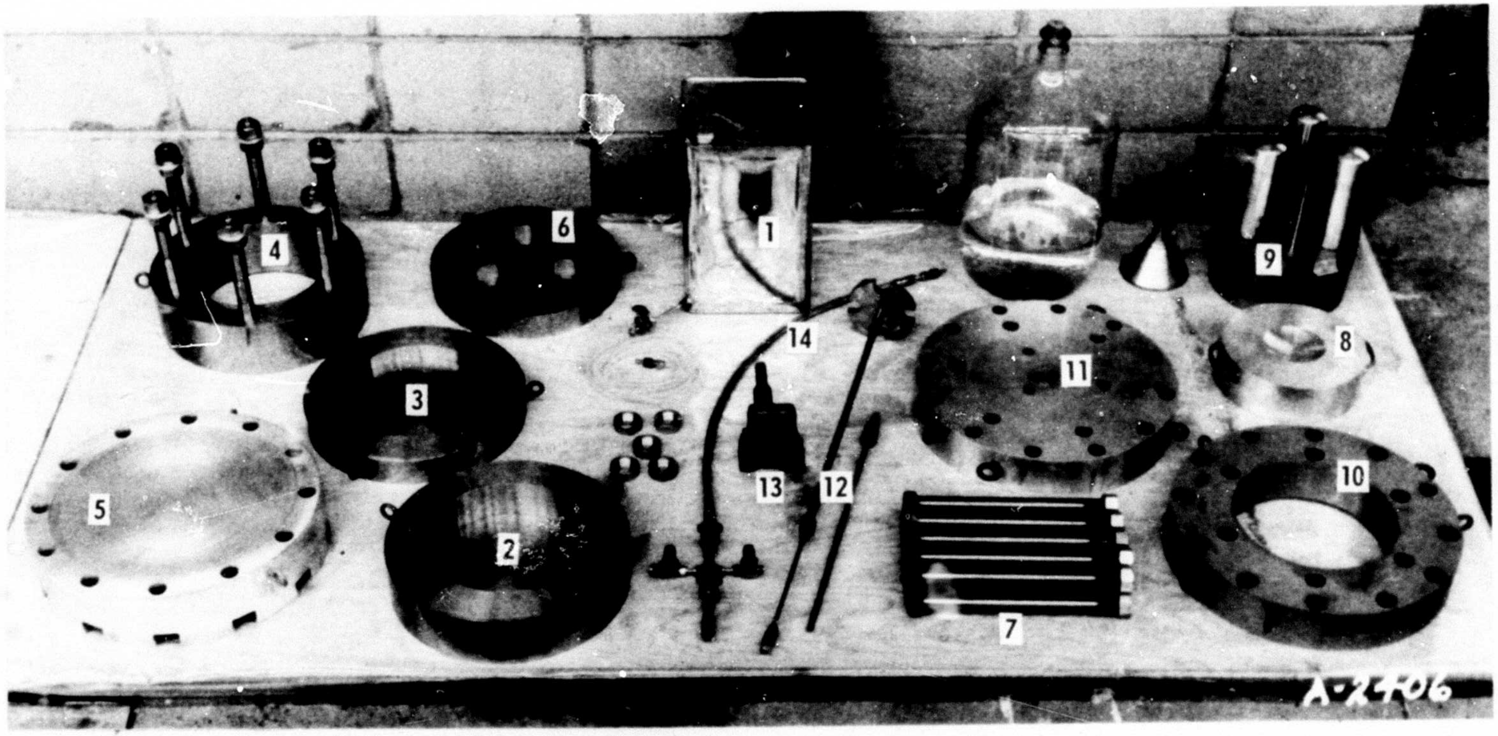
4.1 Introduction

4.1.1 General Background

The WES 10-in.-diam, one-dimensional compression device was fabricated in accordance with the original design considerations discussed in Chapter 3. Drawings of the device assembled in the two configurations are shown in Figs. 14 and 17, and a photograph of the various components comprising the device is shown in Fig. 31.

When the fabrication of all the components was completed, a program was initiated for the purpose of evaluating the performance of the one-dimensional compression test facility. For ease in reference and convenience in presentation, the results of the evaluation program have been divided into groups which correspond to those used in the design of the device, and they are discussed accordingly. A chronological framework for these discussions is presented below.

The first steps in the evaluation program actually preceded the fabrication of the original device. The load-deformation test on the Dynapak foundation, which resulted in the rejection of a simple fixed-point reference for the LVDT displacement transducer, has already been mentioned (Section 3.6). The next step, which occurred while the device was being fabricated, resulted in an important setback to the facility. It became apparent that the contractor selected to develop the 100-kip dynamic loading machine would be unable to develop a loader in accordance with WES's control specifications (Section 3.4), and the contract calling for



COMPONENTS COMMON TO BOTH INITIAL CONFIGURATIONS

1. WATER SUPPLY CONTAINER
2. SOIL CONTAINER FOR $2\frac{1}{2}$" SPECIMEN
3. SOIL CONTAINER FOR 1" SPECIMEN
4. FLUID CONTAINER WITH LVDT COIL SUPPORT COLUMNS
5. LOWER ASSEMBLY CONTAINER PLATE
6. LVDT COIL SUPPORT PLATE
7. ASSEMBLY BOLTS FOR 1" SOIL CONTAINER

*CORE HOUSINGS ARE COMMON TO BOTH CONFIGURATIONS

COMPONENTS FOR INITIAL PRINCIPAL CONFIGURATION

8. UPPER PISTON
9. LOWER PISTON WITH COLUMNS AND CORE HOUSINGS*
10. UPPER ASSEMBLY CONTAINER PLATE

COMPONENTS FOR INITIAL AUXILIARY CONFIGURATION

11. UPPER ASSEMBLY CONTAINER PLATE
12. PISTON AND CYLINDER FOR LOAD GENERATOR
13. GEAR REDUCER (100 TO 1) FOR LOAD GENERATOR
14. HIGH-PRESSURE FLEXIBLE HOSE

Fig. 31. Original equipment components.

the fabrication of this dynamic loading machine was cancelled. As a result, the one-dimensional compression device, which had been designed and was already being fabricated to accommodate a 10-in.-diam specimen, could not be used to test specimens to 1000 psi with controlled loading characteristics, as specified. Instead, the peak pressure capability for the device assembled in the principal configuration became limited to that available with the Dynapak loader, approximately 300 psi.

Several possibilities existed for extending the capability so that it would meet the stated specification (see Section 4.6), and all were considered. Although some of the possibilities were found to be quite feasible and could have been pursued immediately, it was decided instead to complete the fabrication of the device as designed and to proceed with its evaluation. It was anticipated that the results of the evaluation program would provide much information that could be used as a guide in selecting the most promising possibility for extending the capability to higher pressure levels.

4.1.2 Chronological Outline

The evaluation program, as planned and conducted, consisted of three phases. The first phase dealt with the mechanical and physical aspects of the device--whether or not the relatively complex device could be assembled conveniently and rapidly in its two configurations without disturbing the specimen, whether or not failure or leakage would occur under pressure, whether or not the equipment-compressibility effect would be insignificant, etc. The second phase was devoted to the measurement system, particularly the key measurements and the amplifier-recorder system--

calibration of transducers, checks for linearity, repeatability, and drift, analysis of frequency-response characteristics, study of limitations in data reduction, etc. The third phase consisted of actual tests on soil specimens--a simple test series demonstrating some of the capabilities of the Dynapak loader and the device as a whole.

Phase I--Equipment. The evaluation program began with a study devoted to the determination of an acceptable technique for equipment assembly. Although a suitable technique was found, the success of the effort could be demonstrated only by heuristic and qualitative means (see Section 4.2). Nevertheless, the technique was adopted, and the evaluation program was continued.

Later in the program, shortly before the Phase III tests were initiated, the assembly technique which had been selected was evaluated once again, this time quantitatively. The results substantiated the conclusions drawn earlier (see Section 4.2).

Once a suitable assembly technique had been found, the device was assembled in each of its two configurations to determine the behavior of the equipment under pressure (see Section 4.4). Several leaks were observed, but they proved to be minor and easily correctable. None of the components failed.

Although the hydraulic loading system was used to generate the pressure in the fluid chamber for all the failure-leakage evaluation tests, it was found to be an unsatisfactory technique for load generation for the WES one-dimensional compression device (see Section 4.3). Consequently, it was replaced by a very simple pneumatic loading system before proceeding with the evaluation program.

An attempt was made during several of the failure-leakage evaluation tests to determine if the actual lateral strains in the soil-container wall were equal to those predicted in the design considerations. Although the attempt proved to be unsuccessful, a renewed effort was devoted to this aspect of equipment evaluation later in the evaluation program (during the equipment-compressibility study), at which time it was found that the lateral strains were very nearly equal to those predicted by theory for an axially infinite elastic cylinder. The results of the lateral-strain evaluation are included in the discussions dealing with the evaluation of the lateral-stress strain-gage transducer (see Section 4.5).

Phase I of the facility-evaluation program was concluded by conducting a series of tests to evaluate the effect of equipment compressibility on the specimen-deformation measurement in the two equipment configurations. The design assumption that the effect would not be significant was found to be grossly inaccurate. The results of the first equipment-compressibility test indicated that not only were the equipment deformations more than thirty times the anticipated values, but also the nature of the deformations was highly erratic.

The results of the equipment-compressibility study which followed made it clear that the deformations observed in the first test had stemmed from several sources. At first, it was difficult to identify the various sources. However, as each source was identified and then eliminated, the results of the equipment-compressibility tests became less erratic and easier to interpret, and the sources of the deformations became easier to identify.

Elimination of the various sources of equipment deformations resulted in several modifications to the one-dimensional compression device. Most of the modifications were associated with the mechanical load-support system (see Section 4.4); some were associated with other portions of the device. The most important examples of the latter were (1) the replacement of the pneumatic load-application system (used in conjunction with the auxiliary equipment configuration) by a pneumatic-hydraulic system (see Section 4.3), and (2) the installation of two accelerometers, one on the coil support plate and one in the lower assembly container plate (see Section 3.6), for the purpose of providing information regarding the relative displacement between the LVDT coils and the base of the soil container (see Section 4.5).

The results of the key equipment-compressibility tests are presented in Appendix B, and are discussed in Section 4.4. The final equipment-compressibility tests on the modified one-dimensional compression device concluded Phase I of the evaluation program.

<u>Phase II--Measurement System</u>. Although both the flush-mounted pressure transducer and the LVDT displacement transducer were first used in the equipment-compressibility study (before that, Bourdon-type pressure gages were used to determine the chamber pressure), these two transducers and the amplifier-recorder system used in conjunction with them were not subjected to an intensive evaluation until the first phase of the preliminary testing program had been completed. The results of the evaluation showed that the two key measurements were being made satisfactorily in all respects (Section 4.5).

The transducers selected for the five other measurements

thought to be desirable (see Section 3.6) were not evaluated as thoroughly as were the two transducers used for the key measurements. Furthermore, there was no specific time set aside for their evaluation. In general, evaluation tests were conducted on an available time basis, and the extent of the evaluation was determined by the requirements of the immediate, rather than the long-range, application (Section 4.5).

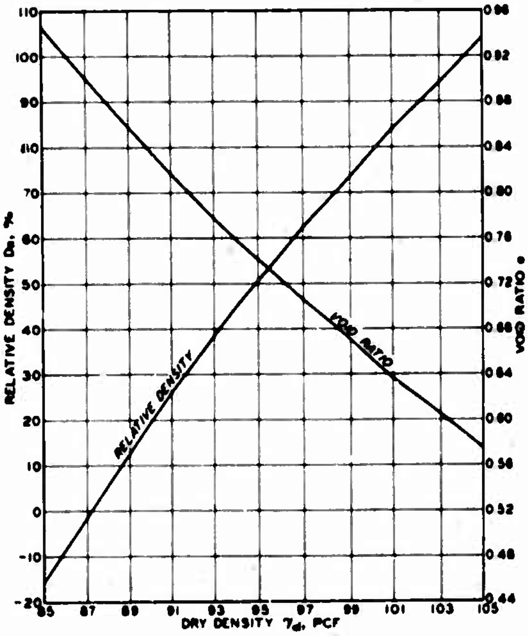
Phase III--Typical Tests. When both the equipment and the measurement system had been satisfactorily evaluated, a few actual tests were conducted with the device assembled in each of the two test configurations. The purpose of the tests was to provide an indication of the performance of the Dynapak loader and that of the device as a whole, although some information was also obtained about the performance of individual elements within the device. It was found, for example, that there was occasionally some internal leakage from the fluid chamber to the soil chamber (Section 4.4), that it would be advisable to add a barrier chamber to the pneumatic-hydraulic load-application system (Section 4.3), that the frequency-response characteristics of the flush-mounted pressure transducer and the LVDT displacement transducer were satisfactory (Section 4.5), etc. The results of the test series, as they bear upon the performance of the device as a whole, are discussed in Section 4.6.

All the tests were conducted in the modified device (Figs. 15, 16, and 18). The short-duration loadings were applied by the Dynapak loader (Figs. 21 and 38), and the long-duration loadings were applied by the pneumatic-hydraulic load-application system (Figs. 24 and 37, without the barrier chamber). A 2-psi seat load was used for all tests.

The soil used for all but one of the tests (Test No. A01A05, for which a steel specimen was used) was an air-dried, uniform, fine sand (SP), locally referred to as Reid-Bedford Model Sand. Selected properties of the material are shown in Fig. 32. The specimens were placed in the soil chamber by a raining technique (Fig. 19a) in which the sand falls through a series of holes uniformly distributed over the area of a circular plate and then through a set of nine screens (Fig. 33). The results of a fairly extensive placement study (approximately 100 tests, which were conducted with the multiple orifice sand sprinkler and the 10-in.-diam, 1-in.-deep soil chamber) showed that, for the high-relative-density range (90 to 100 percent), the density deviation in any given specimen is no greater than 0.3 pcf, with a tendency for the lower densities to occur near the wall (Marshall and Schindler, 1967). The average density from specimen to specimen was found to vary from ±0.1 pcf for the higher densities to ±0.2 pcf for the lower densities, in the high-relative-density range.

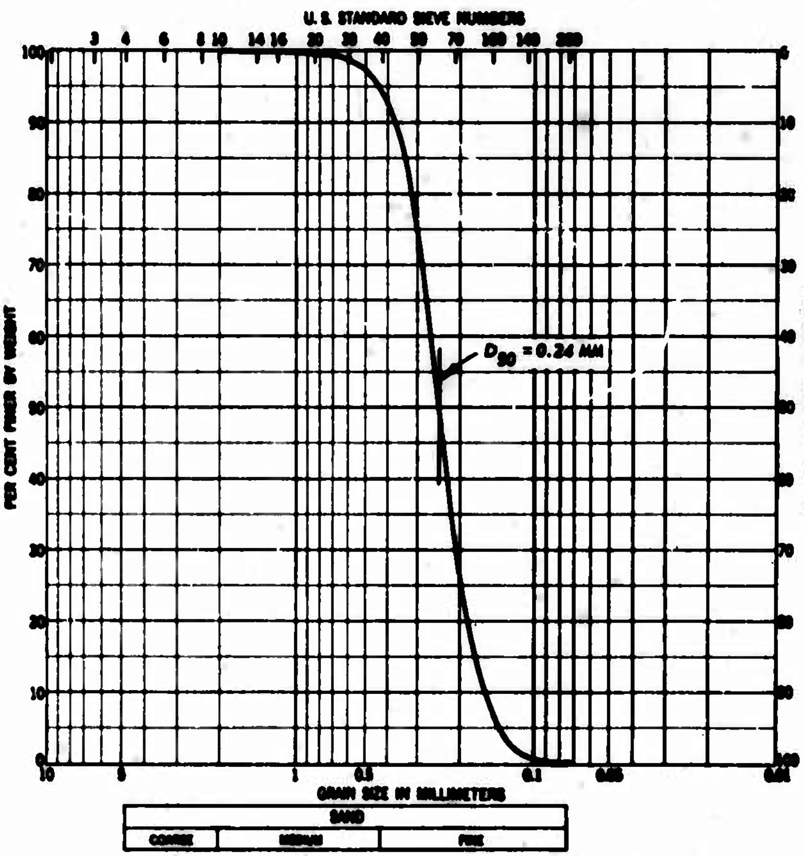
All the sand specimens in the test program were placed at a relative density of 93 percent (±1 percent) except one (for Test No. A10A03), which was placed at a very low density so that the effect of side-wall friction could be determined for a loose specimen. A water-content determination was made on the material from which each specimen was prepared. The water content and density of the actual specimen were determined after the test.

The results of all the tests conducted are presented in Appendix B. During the long-duration tests, the data were recorded at intervals (except at the beginning and at the end of the pressure rise



a. AGGREGATE CHARACTERISTICS

b. PHOTOMICROGRAPH, 25 ×
(1 MM)



c. GRAIN-SIZE DISTRIBUTION CURVE

Fig. 32. Selected properties of Reid-Bedford Model Sand.

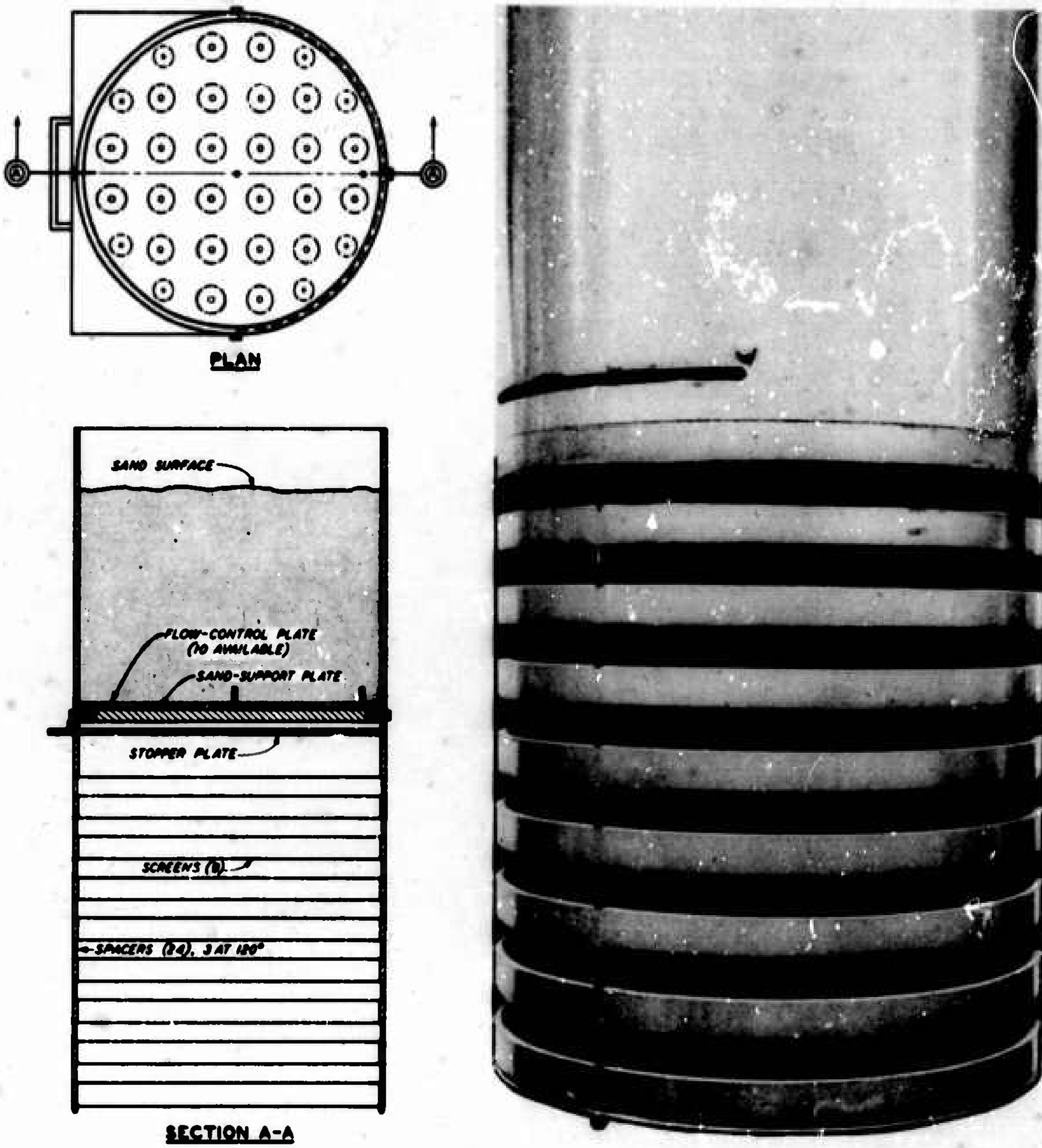


Fig. 33. Multiple orifice sand sprinkler (MOSS).

and pressure decay, where the data were recorded continuously), and readings were taken at each interval. During the short-duration tests, the data were recorded continuously, and readings were taken every millisecond and wherever a sudden change in the signal occurred (e.g., at the peak of an oscillation). Points for the stress-strain curves shown were obtained by plotting all the stress and strain readings, and then drawing the best smooth curve through the points. None of the data has been corrected for equipment compressibility. Sample oscillograph records for a short-duration test and for a long-duration test are presented in Figs. 47 and 48, respectively.

4.2 Equipment Assembly

4.2.1 Description of Technique Used

When fabrication of the one-dimensional compression device was completed, a study was undertaken to determine an acceptable technique for equipment assembly. The study was successful, and a satisfactory technique was found. Although the technique was modified in various ways as the facility-evaluation program progressed, its essential features remained the same. A brief description of the technique, as it applies to the assembly of the device in the two modified test configurations (Figs. 15 and 18), follows.

General. Since the equipment is fairly massive and difficult to handle, an electric hoist (suspended from a crane beam) is used during the assembly. Although the hoist is operated electrically to raise the various equipment components and to lower them until they are almost in position in the assembly, final lowering of each component is accomplished

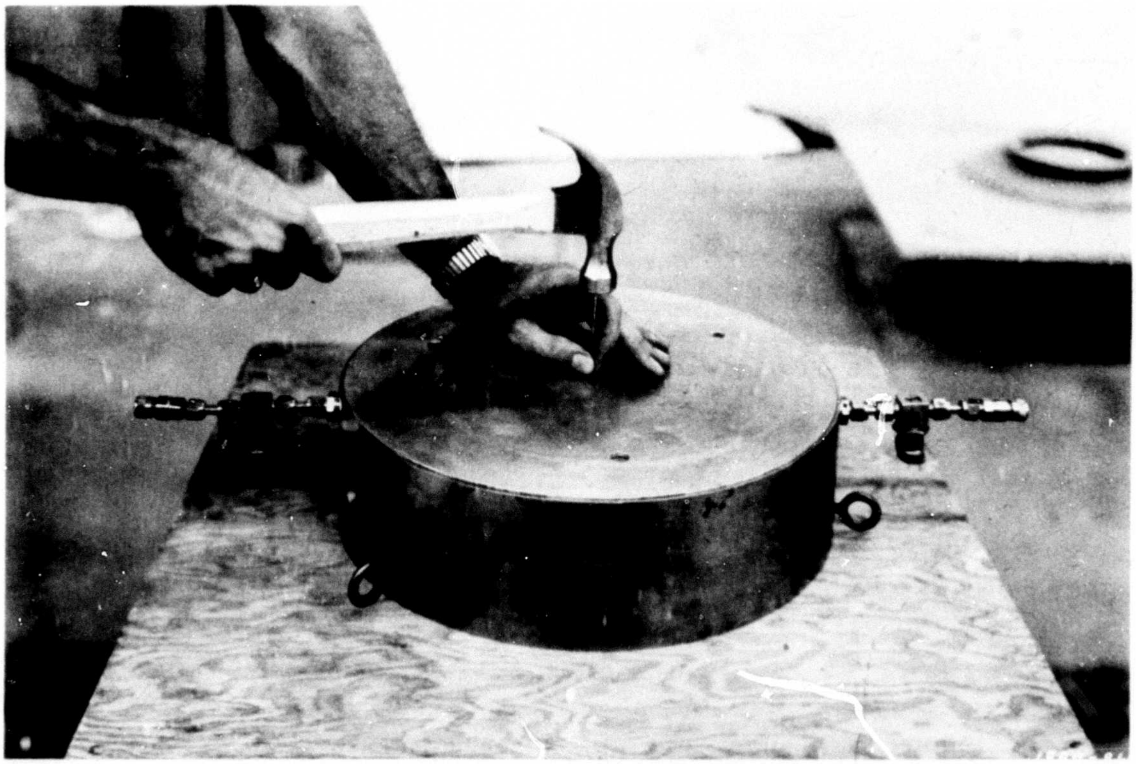
mechanically, by means of a large (7-in.-travel) turnbuckle attached to the hook of the hoist.

Lateral alignment of adjacent pieces in the assembly is assured by the shear connections between all members. Rotational alignment is achieved by means of a reference line scribed on each of the components.

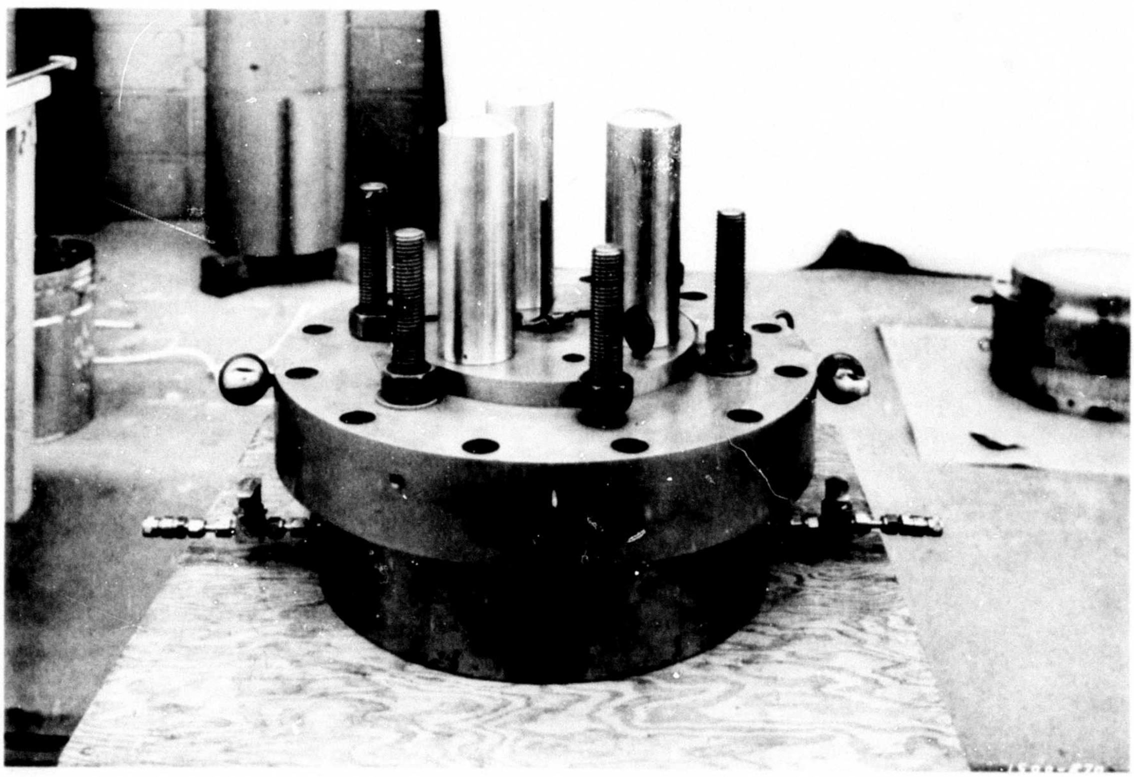
Subassembly Preparation. The key feature of the assembly technique selected is the use of a preassembled subassembly. The subassembly (Fig. 34), which includes the fluid container, the flexible membrane (bonded to the fluid container), the LVDT core systems (supported on the lower piston by crocodile clamps), the upper assembly container plate, the LVDT coil support columns, the lower piston (supported on the upper assembly container plate by two brackets), and the piston assembly columns, is prepared only when it becomes necessary to change the rubber membrane. Once prepared, it can be retained in its assembled configuration.

When it becomes necessary to change the rubber membrane, the subassembly is disassembled, and the old membrane is removed. After the bottom surface of the fluid container has been cleaned and a new membrane has been bonded to the fluid container, the locations of the LVDT's are marked (Fig. 34a), and holes are punched in the membrane at these locations. (LVDT No. 0 was the only one being used when the photographs were taken.) The core systems are then connected to the membrane (Fig. 27), and the subassembly is prepared (Fig. 34b).

Specimen Placement. The first step in the actual assembly procedure is the placement of the specimen into the soil chamber of the



a. MARKING LOCATIONS OF LVDT'S



b. COMPLETED SUBASSEMBLY

Fig. 34. Subassembly preparation.

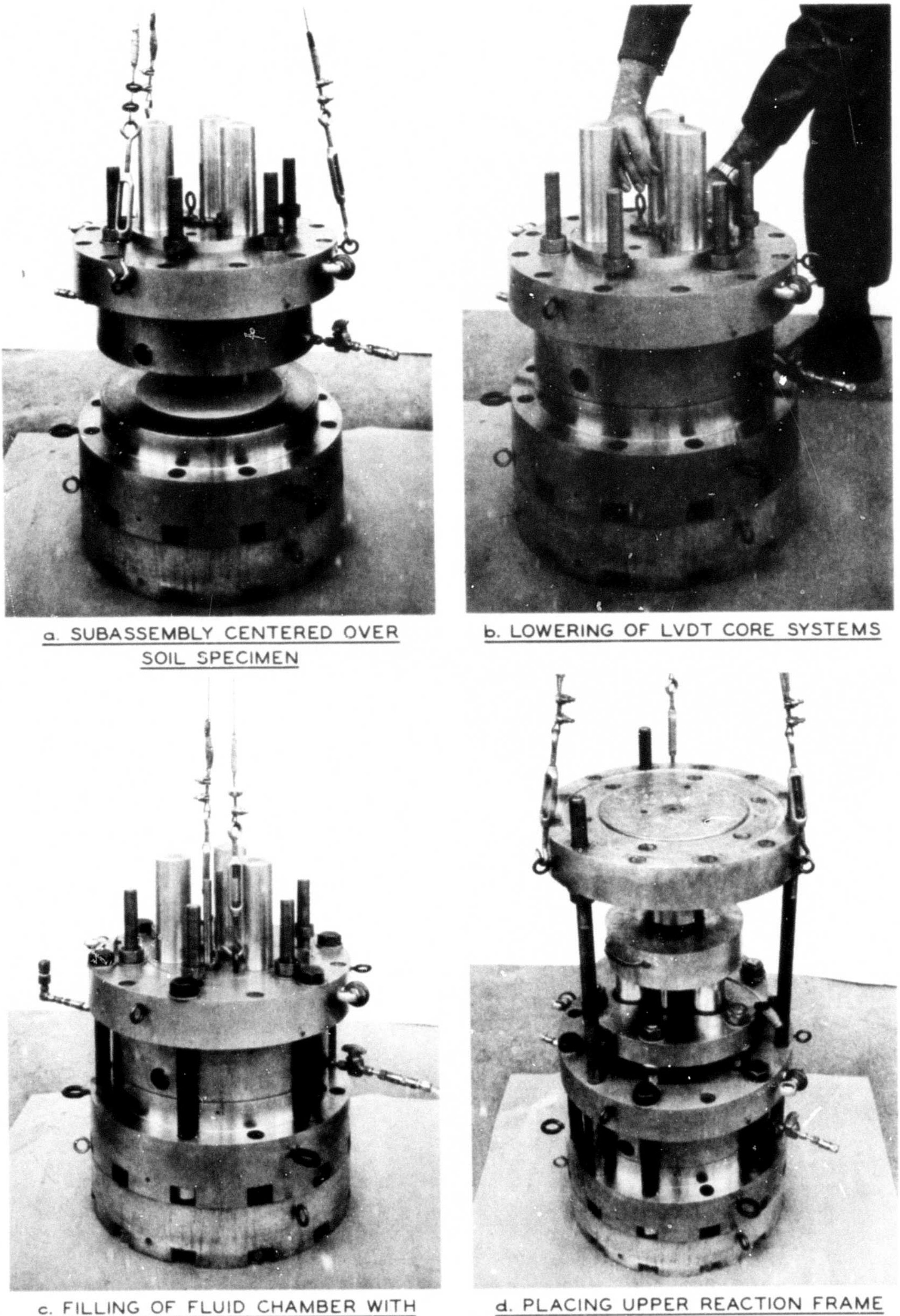
appropriate soil container-lower assembly container plate (e.g., see Figs 19 and 20).

Equipment Assembly--Part I. After the specimen has been placed into the soil chamber, the subassembly is centered over the soil container-lower assembly container plate (Fig. 35a) and leveled. Machined spacers are then placed around the lip of the shear connection at the top of the soil container wall (Fig. 35a), and the subassembly is slowly lowered into position onto the spacers.

Equipment Assembly--Part II. The crocodile clamps supporting the LVDT core systems on the lower piston are removed, and the core systems are gently lowered (approximately 1/16 in.) onto the specimen surface (Fig. 35b). (After the photograph shown in Fig. 35b was taken, it was observed that the subassembly and the soil container-lower assembly container plate had inadvertently been misaligned. The core system was then raised, the misalignment was corrected, and the core system was again lowered onto the specimen surface.)

When all the core systems have been lowered onto the specimen surface, support of the subassembly is once again transferred to the electric hoist, and the spacers are removed. The subassembly is lowered onto the soil container-lower assembly container plate, and the four core housings are carefully threaded into the lower piston. The assembly bolts are then placed in position and tightened.

Equipment Assembly--Part III. Support of the lower piston is transferred to the electric hoist, and the brackets which had supported the lower piston on the upper assembly container plate are removed. The lower piston is then lowered into position, and the fluid chamber is



a. SUBASSEMBLY CENTERED OVER SOIL SPECIMEN

b. LOWERING OF LVDT CORE SYSTEMS

c. FILLING OF FLUID CHAMBER WITH PRESSURE FLUID

d. PLACING UPPER REACTION FRAME PLATE IN POSITION

Fig. 35. Equipment assembly.

filled with pressure fluid (Fig. 35c) until the level of the fluid reaches the top of the core housings. The bleed screws are then placed in position to seal the fluid chamber completely.

After the coil support plate has been placed and locked in position, the upper piston is placed on the piston assembly columns to complete the assembly of the device in the principal configuration. When the device is assembled in the auxiliary configuration (as in Fig. 35), the assembly is completed by placing the reaction frame columns and the upper reaction frame plate in position (Fig. 35d). A photograph of the assembled device in position for a long-duration test appears in Fig. 37.

Equipment Relocation. After the assembly of the device in the principal configuration has been completed, the device is moved into position under the Dynapak loader by means of a lever system specifically fabricated for the purpose (Fig. 36). A photograph of the assembled device in position for a short-duration test appears in Fig. 38.

4.2.2 Characteristics of Technique Used

The technique described above for assembling the fairly complex one-dimensional compression device was considered to be acceptable because it was simple to use, required little time and effort, and resulted in little (if any) specimen disturbance.

Time and Effort. Because the device was designed for practical as well as for research applications, it was thought to be especially important to minimize the time and effort required for equipment assembly prior to each test. Using the technique described above, one man (with assistance from another man at a few important stages of the

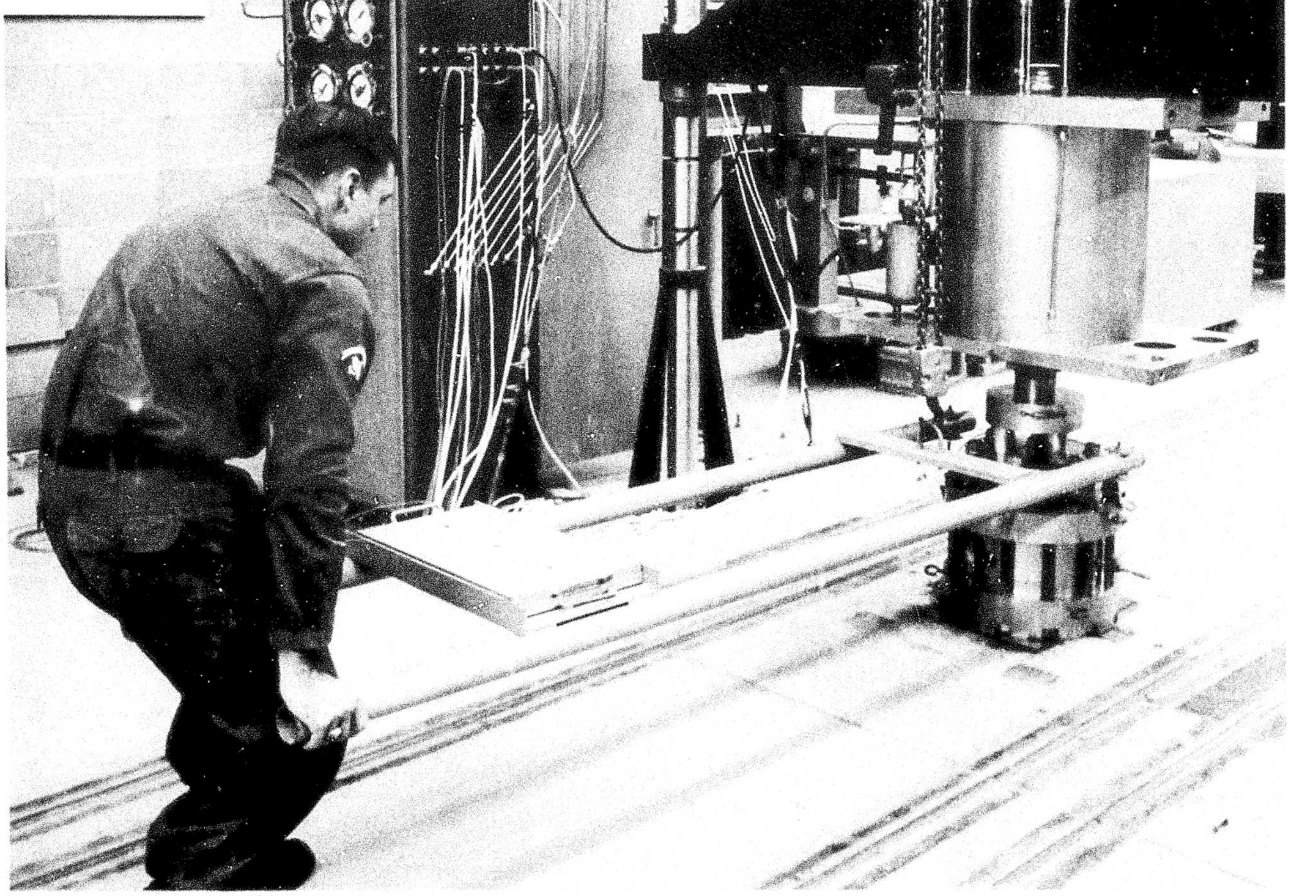


Fig. 36. Equipment relocation.

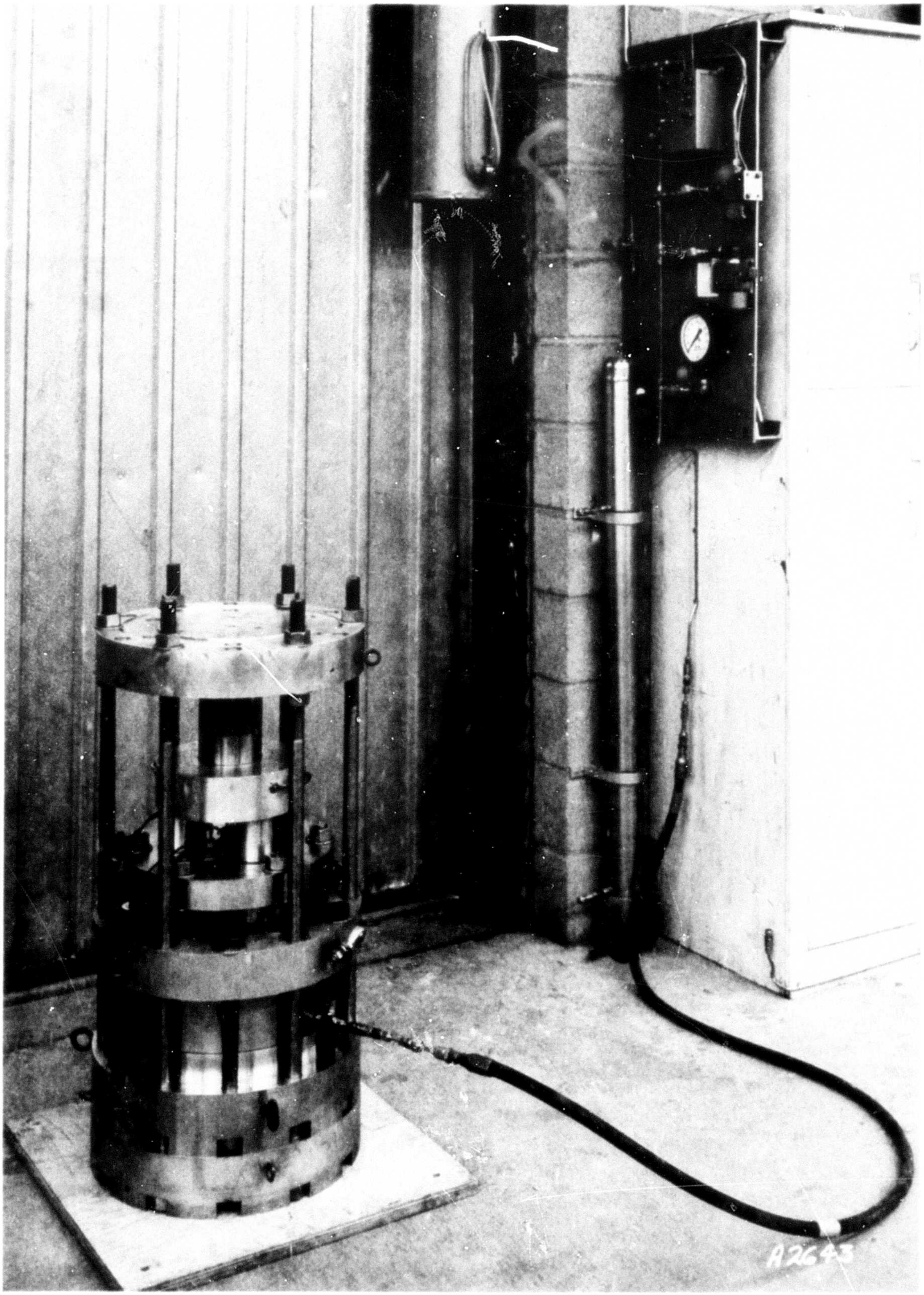


Fig. 37. Assembled device in position for long-duration test.

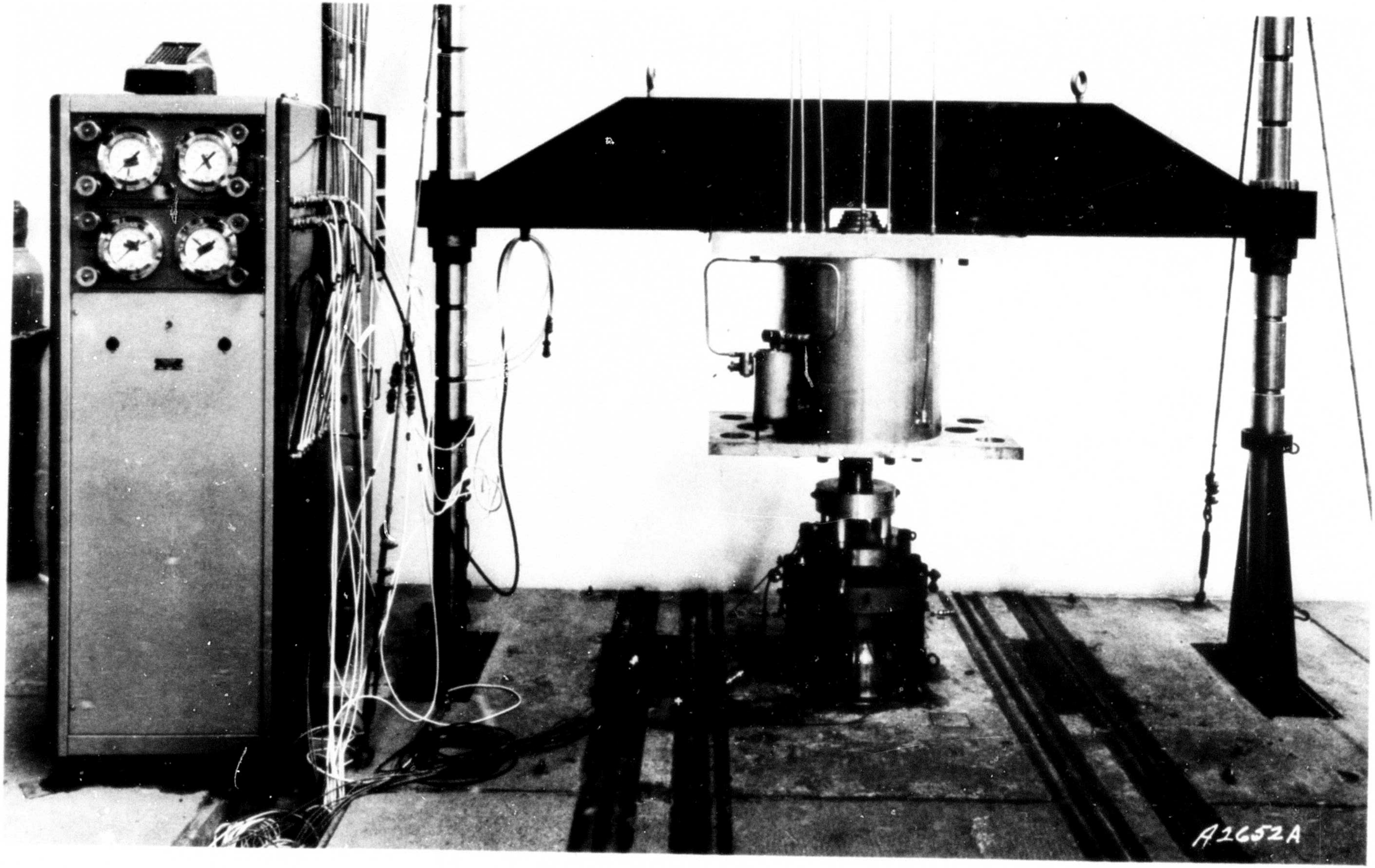


Fig. 38. Assembled device in position for short-duration test.

assembly) can complete the entire assembly for a routine test in less than an hour. The only appurtenances required are the electric hoist, which was already available in the WES laboratory, the lifting system (turnbuckles, braided-wire cables, eyebolts, etc.), and the lever system.

Specimen Disturbance. From the time a specimen is placed in the soil chamber until the time the overburden-simulating initial pressure is applied, the specimen may be subjected to several sources of disturbance--jarring of the equipment as each component is added to the assembly, seating of the LVDT core systems on the specimen surface, jarring of the core rods (and, thereby, the specimen) as each component is added to the assembly, jarring of the equipment as the assembly bolts are tightened, and jarring of the equipment as the assembly is moved into position under the Dynapak loader.

The assembly technique described above clearly results in little or no specimen disturbance. Because equipment components are added to the assembly statically by means of a turnbuckle, there is no jarring of the equipment from this source. The preassembled subassembly places the four LVDT core systems in their proper locations, vertically (very nearly) as well as radially and tangentially, without contact to the specimen surface, at the same time that it places the equipment components surrounding the core systems (particularly the lower piston) in the assembly. Consequently, there is no specimen disturbance when the core rods are seated, since seating simply requires slowly lowering the core system approximately 1/16 in.; nor is there an opportunity for jarring of the core rods after the core systems have been seated. (The small, light core housings are easily threaded into the lower piston without

jarring the core rods.) The use of a torque wrench with a long lever arm to apply small increments of torque sequentially to the various assembly bolts makes it possible to tighten the bolts (to 100 ft-lbs) without jarring the massive equipment assembly. If the equipment is assembled in the immediate vicinity of the Dynapak loader, the assembly can be raised statically by means of the lever system and placed in position under the Dynapak loader without the need for any motion of the crane beam; with this technique, there is little or no jarring of the equipment as the assembly is moved under the Dynapak loader.

An indication of the amount of disturbance actually caused by each of the sources listed above was obtained by disassembling the equipment after each step in the assembly and comparing the appearance of the specimen surface with its appearance after the previous step in the assembly. Dry, 1-in.-thick sand specimens at an initial relative density of 0 percent (approximately) were used for the study. The comparisons were made by visual observation, with a steel straightedge across the top of the soil container as a reference.

The results of the study indicated that the amount of disturbance was very small. The only change in the appearance of the specimen surface was observed when support of the LVDT core systems was transferred from the lower piston to the specimen surface. When the equipment was disassembled after this step in the assembly procedure, the area of each disc was clearly marked by a smooth appearance of the specimen surface and a very slight ridge separating the smooth area from the rest of the specimen surface. Although the area where each of the discs had been supported clearly was different in appearance from the rest of the specimen

surface, there was no indication of an indentation into the specimen surface at these locations. (The stress applied to the specimen surface by the weight of the Plexiglas core system used in the study was approximately 0.02 psi. The stress applied by the heaviest metallic core system available, Fig. 27c, was approximately 0.1 psi.) The distance between the straightedge and the smooth areas appeared to be the same as the distance between the straightedge and the rest of the specimen surface (except at the locations of the ridges, where the straightedge actually penetrated slightly into the sand).

Although the amount of disturbance to which a specimen might be subjected during equipment assembly had been demonstrated to be quite small, there was no quantitative information available to indicate how small. This information was obtained later in the evaluation program when the equipment was intentionally subjected to several types of disturbance, and the displacement of the specimen surface as a result of each type was measured. Dry, 1-in.-thick sand specimens at initial relative densities of 0 and 90 percent (approximately) were used for the study.

The results of the study substantiated the conclusions which had been drawn from the results of the earlier qualitative study. When the equipment containing the loose sand specimen was raised with the electric hoist, moved approximately 30 ft with the crane beam, jarred, and placed into position under the Dynapak loader, the total amount of surface displacement measured was approximately 1.5 mils (corresponding to a change in density of only 0.125 pcf). The corresponding displacement value for the dense specimen was only 0.04 mil. When the equipment containing the loose sand specimen was raised with the turnbuckle and placed under the

Dynapak loader without moving the crane beam (very much), the total amount of surface displacement measured was only 0.07 mil. No displacement was observed when the equipment with the dense specimen was handled in this way. Clearly, the amount of specimen disturbance which occurs during equipment assembly is negligible for all soils of interest.

4.3 Load-Application System

4.3.1 Principal Configuration

The design of the WES one-dimensional compression device was based on the assumption that two dynamic loading machines would be available as load generators. One, the Dynapak, was already available, and the other, a 100-kip loader, was on order. When the design of the device was completed, however, it was found that the contractor selected to develop the 100-kip dynamic loading machine would be unable to develop a loader in accordance with WES's control specifications (Section 3.4). The contract calling for the fabrication of this dynamic loading machine was cancelled, leaving the Dynapak loader, with a peak-load capability of approximately 25 kips (300 psi on a 10-in.-diam specimen), as the only load generator for the principal configuration of the one-dimensional compression device.

A schematic drawing of the Dynapak loader is presented in Fig. 21, and a photograph of the one-dimensional compression device in position for a short-duration test is shown in Fig. 38.

Pulse Characteristics. A typical Dynapak-generated pressure pulse is shown in Fig. 39. The rise portion of the pulse is characterized by a straight-line pressure-time relationship, which is interrupted at fairly regular intervals by a single low-amplitude oscillation. The decay

portion of the pulse is nearly linear with time throughout most of its duration. The initial part of the decay portion (or, the initial part of the dwell portion, when a dwell is used) is characterized by the same low-amplitude oscillations as is the entire rise portion of the pulse, and the final part of the decay portion is characterized by an ever-decreasing rate of decay.

The typical pressure pulse can be considered to consist of a straight-line rise portion and a straight-line decay portion with over-riding low-amplitude oscillations. In contrast to the true rise time, which represents the total time in which the pressure rises from its initial value to its peak value, an effective rise time is defined as the pressure increment (i.e., the change in pressure) divided by the linear rate of rise, a far more descriptive and useful characteristic. Similarly, an effective decay time is defined as the pressure increment divided by the linear rate of decay.

The amplitude of the oscillations is always small, and there is little or no effect on the stress-strain relationship measured (see Section 4.6). However, the oscillations do have a significant effect on the rise time of a typical pressure pulse; for example, although the effective rise time of the pulse in Fig. 39 is approximately 16 msec--the shortest rise time permitted for the test according to Equation 2.1--the true rise time is approximately 30-35 msec. Unfortunately, these oscillations represent the free-vibration component of the transient response (see Section A.6), and there is little that can be done to modify them with the existing configuration.

Control Capabilities. The control capabilities of the Dynapak

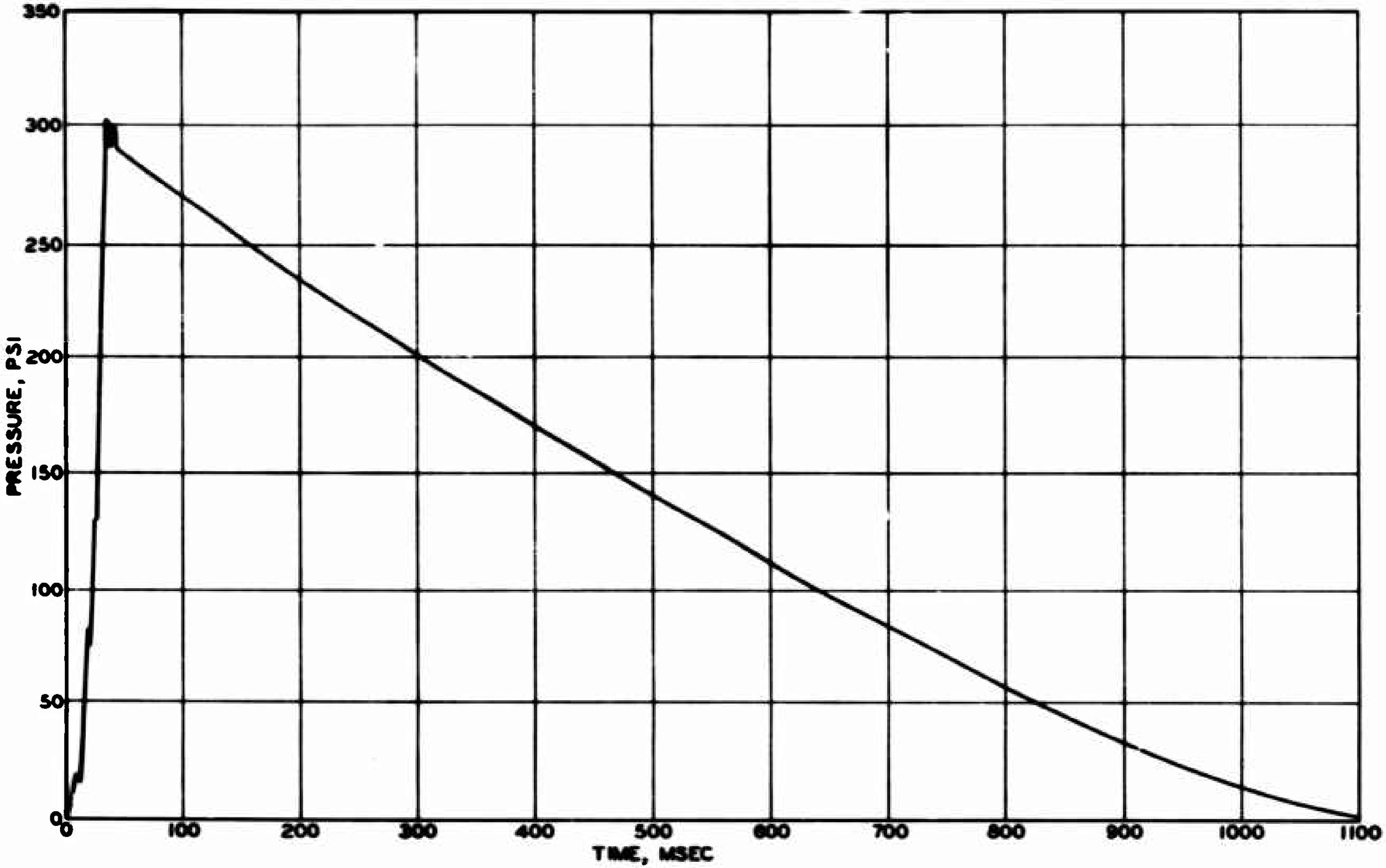


Fig. 39. Typical Dynapak-generated pressure pulse (Test No. A01P04).

loader are quite good on a day-to-day basis but only fair on a long-term basis. This means that when a given set of valve and timer settings results in a certain pressure pulse one day, the same settings will result in very nearly the same pulse the next day, but only in a similar pulse at some time later. Consequently, if the characteristics of a given pressure pulse must be accurately preset, the required settings are determined by trial and error calibration tests just prior to the actual test. This results in very little inconvenience during an active testing program, since the assembly from the test just prior to the one in question can be used for the calibration tests.

When calibration tests are used, it is possible to preset both the peak pressure and the time characteristics of the pulse within several percent of the desired values. Unfortunately, when the test series reported herein was conducted, there was a small leak in one of the Dynapak control valves. Since it is the policy of the operating personnel not to disassemble the Dynapak loader unless absolutely necessary, attempts were made to compensate for the slow leak by anticipating its magnitude and setting the controls accordingly. Even under these somewhat less than ideal conditions, control of the peak pressure and of the time characteristics of the pulse was quite good.

An indication of the degree of control which is available can be obtained from the pressure pulse of Test No. A01P04, replotted on a larger scale for convenience as Fig. 39. This pressure pulse was designed to simulate (by impulse) the surface air-blast loading from a 100-MT nuclear surface burst at the 300-psi overpressure level. The fastest permissible effective rise time for the test was 16 msec, and this was the

value selected. An effective decay time of 1 sec was selected to simulate the impulse (approximately 150 psi-sec). It is apparent from Fig. 39 that, in spite of the presence of a small leak in the control system, it was possible to preset the characteristics of the applied pulse accurately.

The control settings for Test No. A01P04 were obtained on a trial and error basis from calibration tests conducted for this purpose. More than one month after the test was conducted, an attempt was made to conduct a repeat test, Test No. A01R03, with the same control settings. The pressure pulse obtained is compared with the pressure pulse from Test No. A01P04 in Fig. 40.

It appears as if the Dynapak loader can provide the following control capabilities for a 25-kip load applied to the one-dimensional compression device (which, as shown in Section A.6, has an effective spring constant of approximately 1000 kips per in.):

(1) Effective Rise Time: 1 msec to ∞

(2) Hold Time: 0 to ∞

(3) Effective Decay Time: 30 to 10,000 msec

Test Nos. A01P01 (Fig. 125) and A01P03 (Fig. 127) were conducted with the minimum decay-valve setting on 1- and 2-1/2-in.-thick specimens, respectively. Test No. A01P02 (Fig. 126) was also conducted with the minimum decay-valve setting, but with a 1-sec hold (or dwell) time. (Note the small leak.) In all three tests, the effective rise time preset was the fastest that was permissible.

It is apparent that with the control capabilities available it is possible to simulate and certainly bracket nearly all load pulses of interest.

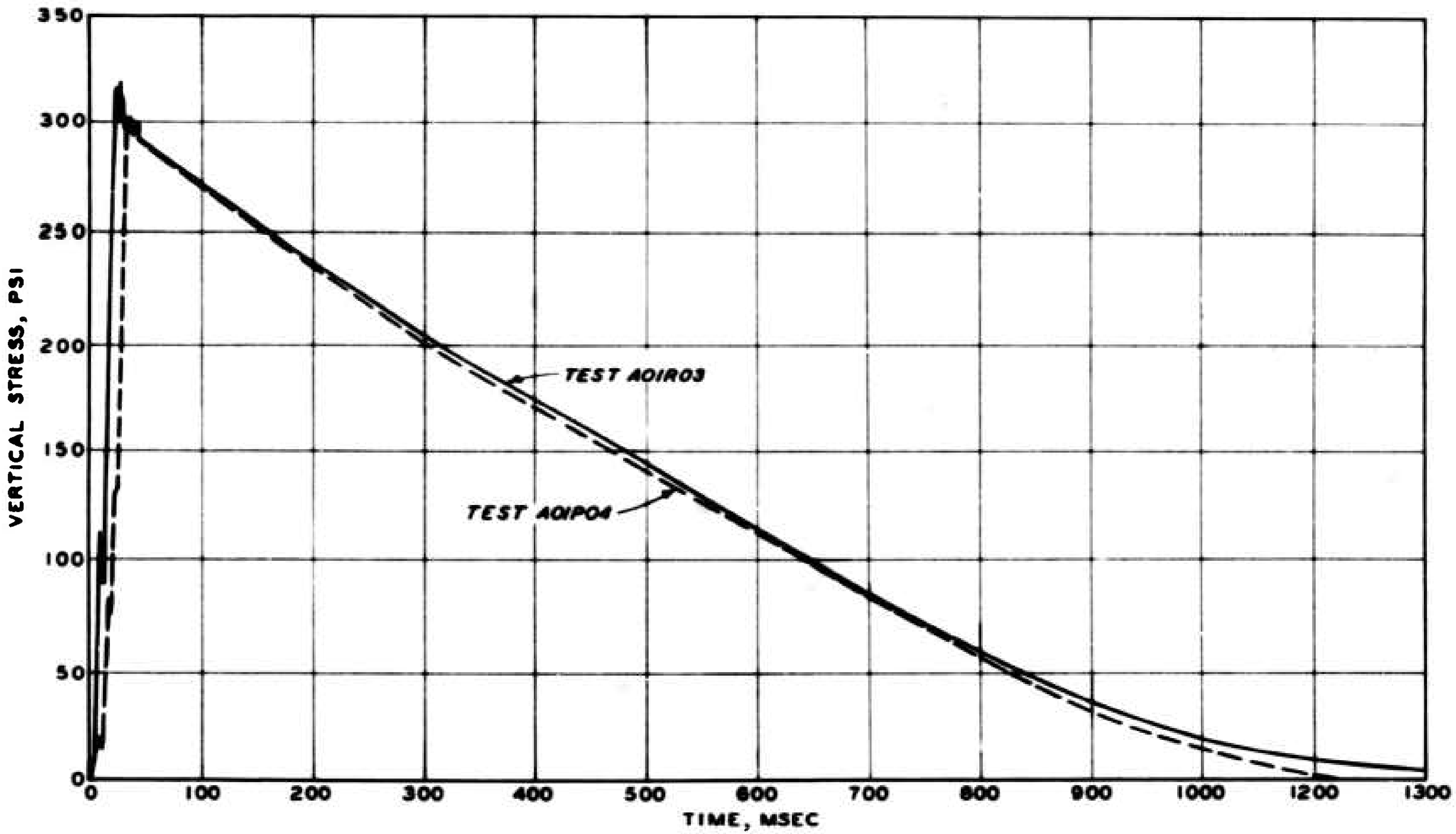


Fig. 40. Comparison of two pressure pulses with same control settings.

4.3.2 Auxiliary Configuration

Although the selection of a particular type of load-application system for use in conjunction with the auxiliary configuration was based on considerations such as simplicity, safety, availability of components, ease of operation, and versatility, the only requirement specified for the load-application system was that it be able to develop pressures to 1000 psi in the fluid chamber. Consequently, once a particular load-application system had been selected and installed, the major concern was whether or not it could develop pressures to 1000 psi in the fluid chamber without adversely affecting the performance of the device.

Hydraulic System. The original load-application system selected for use in conjunction with the auxiliary configuration (Fig. 41) was evaluated simply by using it for the first of the Phase I tests of the facility-evaluation program.

Although the hydraulic load-application system was used for all the failure-leakage evaluation tests, it was apparent after the first test that this system would not be satisfactory for general use. When the full travel of the piston had been completed, the pressure had been raised to only several pounds per square inch. Fortunately, it was possible to refill the cylinder and continue the pressurization with the valving arrangement used (Fig. 41); however, this method of load application was time-consuming and tedious, as four or five cycles of piston travel and refilling were required to generate a pressure of 1000 psi.

There had clearly been an oversight in the design of the loading system. The volume of the cylinder (i.e., the product of the cylinder area and the piston stroke) had been selected on the basis of the

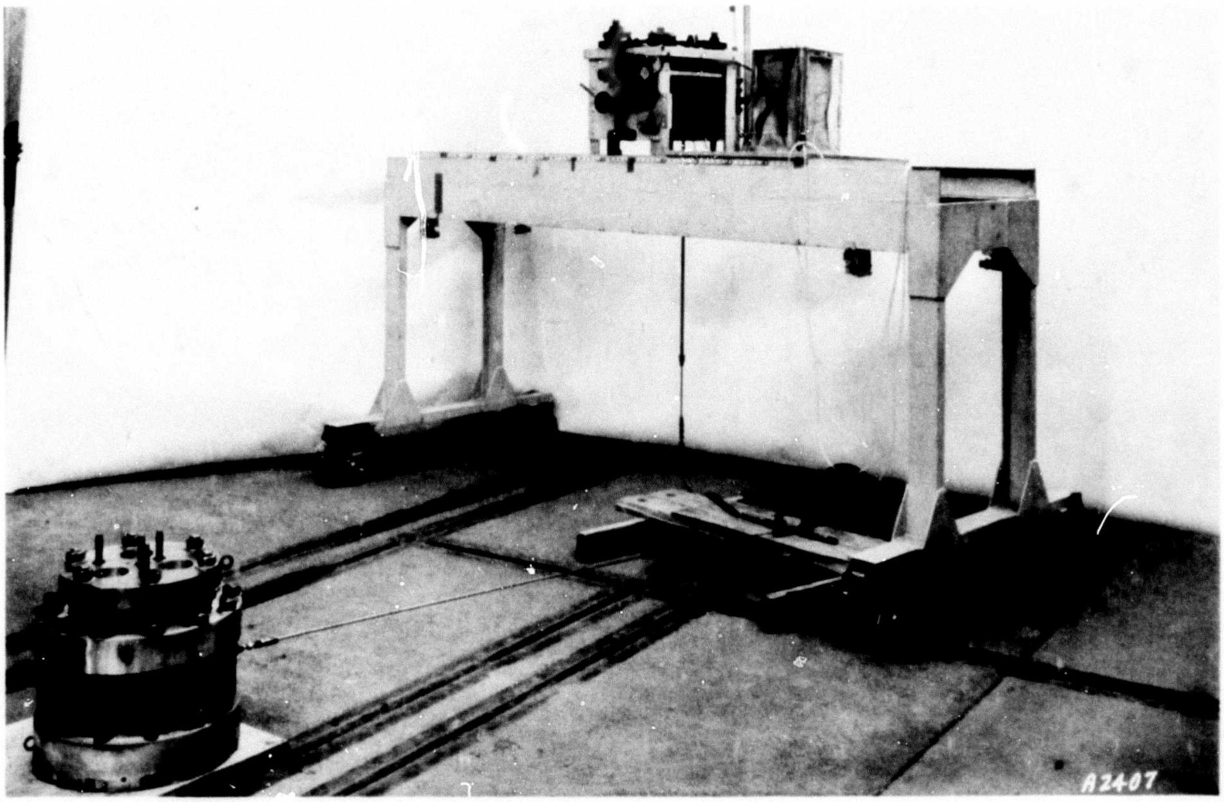


Fig. 41. Hydraulic load-application system in operation.

anticipated compression of the known volume of water and the estimated volume of air in the load-application system; however, the volume change resulting from the deformation of the very large specimen had been overlooked. Since the area of the cylinder could not be enlarged without exceeding the load capability of the mechanical system and since the length of the piston stroke was restricted by physical limitations, the cylinder could not be redesigned, and the hydraulic system was subsequently replaced by a different type of load-application system.

Pneumatic System. The pneumatic load-application system selected to replace the hydraulic system was evaluated by using it for the equipment-compressibility tests in the facility-evaluation program (Section 4.4). For the first few tests, the load-application system consisted only of a nitrogen bottle and a high-pressure flexible hose. As the program progressed, however, it was found to be desirable to add other components to it (see Section 3.4).

The performance of the pneumatic system, unlike that of the hydraulic system which it replaced, was found to be quite good. Although some leakage problems were anticipated, none occurred. The standard high-pressure lines, fittings, and valves selected were easy to install and safe to use. In fact, nearly all the features considered to be desirable in a load-application system for the auxiliary equipment configuration were represented in the pneumatic system.

In spite of the fact that the performance of the purely pneumatic load-application system proved to be quite good, it became necessary to replace it with a combined pneumatic-hydraulic loading system. The new system retained all the features of the purely pneumatic system except that,

in the new system, the fluid chamber is filled with water before the pneumatic system is used to generate the desired pressure. The change was necessary because the expansion of the high-pressure nitrogen into the fluid chamber caused the LVDT displacement transducer to sense a change in the position of the core which did not result from movement of the core system. It resulted, instead, from contraction of the long LVDT core rod which was immersed in the cooling nitrogen inside the fluid chamber.

The extent of the effect (in time) is demonstrated quite well by the results of Test Nos. 15-17 in the equipment-compressibility study (Figs. 105-107). (It should be noted that at this stage in the equipment-compressibility study, there were still several difficulties which had not yet been identified or corrected.) The three tests were intended to be exactly alike except for the method of load application; the pneumatic system was used in Test Nos. 15 and 16, and the combined pneumatic-hydraulic system was used in Test No. 17. Clearly--even at a rate of pressure increase as slow as 10 psi per minute (100 minutes to 1000 psi)--a creep-type behavior was indicated at peak pressure for the purely pneumatic system but not for the combined system. The creep-type behavior was far more pronounced during the faster tests, especially those in which the peak pressure was held for some time. In Test No. 4, for example, the LVDT reading nearly doubled while the peak pressure was held constant (Fig. 104).

Pneumatic-Hydraulic System. Since the combined pneumatic-hydraulic system was very similar to the purely pneumatic system, there was little evaluation required concerning its performance. Once it replaced the pneumatic system (after Test No. 20 in the equipment-compressibility study), it was used for all tests conducted with the equipment in the

auxiliary configuration and for many with the equipment in the principal configuration.

The only difficulty encountered with this system was the mixing of the nitrogen with the water, which occasionally resulted in erratic decay curves (caused by spurts of pressure decay) and frequently resulted in long delays in the final portion of the decay curve (see, for example, the pressure-time curve for Test No. 17 in Fig. 107). This was corrected, though only after the preliminary testing program had been completed, by the insertion of a barrier chamber in the line to separate the nitrogen physically from the water. During the testing program, spurts of pressure decay were minimized by initiating unloading very gradually.

Any desired pressure-time history can be obtained with the pneumatic-hydraulic load-application system, provided that the test duration is sufficiently long to permit adjustment of the regulating valves during the test. A typical pressure-time history, obtained when the regulating valves are not adjusted during the test, consists of a linear rise portion (with an ever-decreasing rate of increase at the higher pressure levels when the line pressure is less than about 1.5 times the peak pressure for the test) and an exponential decay portion.

The fastest rise time which can be obtained with the pneumatic-hydraulic system in its regular configuration (Figs. 24 and 37) is 100 to 200 msec, and the fastest decay time is several seconds. Of course, it is possible to achieve much shorter loading durations simply by modifying the load-application system so that it is more nearly similar to those used in the fluid-loading devices discussed in Section 2.3. It should be noted that it was necessary to remove the quick-connect valves for the very rapid

loadings, as they were unable to pass the sudden pressure changes.

4.4 Load-Support System

4.4.1 Leakage

The various seals selected for use in the WES one-dimensional compression device were evaluated to a pressure level of 1200 psi. Performance was considered to be satisfactory when no leakage was detectable visually and when a given pressure level could be maintained for a period of 3 hours without a decrease of more than 1 percent in the magnitude of the pressure. Although all the tests specifically conducted to evaluate the leak-control system were conducted with a liquid pressure fluid, the results of the evaluation tests were found to be equally applicable for a gaseous pressure fluid (during the early equipment-compressibility tests, which were conducted with the purely pneumatic load-application system).

External Leakage. Most of the seals in the device itself and in the fittings for it involved the use of an O-ring. All the conventional O-ring installations proved to be trouble free.

At several locations involving a threaded connection--e.g., at the bleed hole-core housing interface and at the flush-mounted pressure transducer-fluid container interface--an attempt was made to use an O-ring without a groove. At first, these O-rings were simply placed at the desired interfaces, and the threaded connections were made very tight. In all cases, leakage occurred in the 500- to 750-psi pressure range. These O-rings were then surrounded by retaining washers, which were designed to simulate conventional O-ring grooves (see Fig. 26), and no further leakage problems were encountered at any of the locations.

Some difficulty was encountered with the O-ring installation at the bottom of the fluid container, which is somewhat unconventional in that (1) the bearing surface for the O-ring is a comparatively flexible material, and (2) the single O-ring is used to prevent flow at both the fluid container-membrane interface and the soil container-membrane interface (Fig. 14). During the failure-leakage evaluation tests, water was occasionally observed to flow out of the device at the fluid container-soil container interface. Since this leakage was not observed in all the tests and since the leakage did not always result in a complete pressure release (but rather in a small pressure decrease followed by a stabilized condition), it was assumed that the leak was caused by some aspect of the assembly procedure. When the problem was investigated, it was found that the cause of the leakage had probably been excessive torquing of the assembly bolts. A maximum torque of 100 ft-lb was established, and no further difficulties were encountered.

Although straight threads with O-ring seals were specified for all threaded connections in the original design, it later proved to be necessary to use pipe threads at several locations (e.g., in the high-pressure flexible hose). As anticipated, the pipe-thread connections did leak at first, no matter how tight the connections were made. However, after the threads had been wrapped with a single piece of teflon tape dope, there was no further evidence of leakage.

There was no difficulty encountered with the cable seal used for the piezoelectric pressure transducer cable.

Internal Leakage. Although the fluid and soil chambers were separated physically by an 0.030-in.-thick, latex-rubber membrane, a hole

was required in the membrane for each of the LVDT core systems used in any given test. The seal designed for these holes (Fig. 27a) was thought to be the same as that used with apparent success in the various fluid-loading one-dimensional compression devices described in Section 2.3. However, several difficulties were encountered with this seal in the WES device.

One of the major difficulties was finding a bonding agent that would adhere to the latex rubber. When the various types of commonly available bonding agents had been found to be unsatisfactory, inquiries were made of all the known manufacturers of latex rubber and of all the known chemical companies dealing in bonding agents. After several types of special bonding agents had been obtained, evaluated, and found to be unsatisfactory--for reasons including poor bond, long set time, and complex application procedure--one was found (GC Electronics Rubber to Metal Cement No. 35-2) which proved to be quite good. It later proved to be more convenient to limit the use of this bonding agent to the rubber disc-membrane interface and the rubber disc-rod interface; the disc for the LVDT core rod was bonded to the bottom of the membrane with 3M Spray Adhesive 77. (The 3M spray adhesive was also found to be convenient for use in bonding the membrane to the bottom of the fluid container.)

Another difficulty encountered with the originally designed seal was the inability to keep the LVDT core rods perpendicular to the horizontal faces of their respective discs. Since the core rods are relatively long, the actual cores at the top of the rods were found to be approximately 1/8 to 1/4 in. from their intended positions. This resulted in complications during the assembly, especially when all four of the LVDT's were used. There was also some concern about the accuracy of the

displacement measurement, as the rubber between the core-rod shoulder and the top of the disc was compressed by the fluid pressure. As a result, it was thought to be advisable to shoulder the core rods directly on the top surface of their discs (Fig. 27b).

Leakage of the pressure fluid into the soil chamber was checked by comparing the water content of the top portion of the specimen after each test with the natural water content of the specimen material (determined prior to the test). Although the performance of the seals was found to be generally satisfactory, occasional leaks were detected. The membrane was carefully examined each time a leak was observed, but there were no indications of any holes. Consequently, it was assumed that the leaks occurred through one of the holes in the membrane for the LVDT core system; the cause of the leakage was attributed to nonuniform distribution or poor application of the bonding material. The frequency of leakage observed for both the original and the modified seals discussed above was thought to be small enough (about 1 time in 20) to permit its continued use, provided that water contents were checked for each specimen.

4.4.2 Equipment Compressibility

The effect of equipment deformations on the specimen-deformation measurement was an important consideration in the design of the WES one-dimensional compression device. With the LVDT coils supported in the fluid container and the fluid container rigidly clamped to the soil container, it was thought that the only contributions to an equipment-compressibility error would be (1) the difference in compression between the central portion and the outside-periphery portion of the soil container

and the lower assembly container plate, and (2) bending of the soil container and lower assembly container plate. The differential compression (or shear deformation) was considered to be limited to the 1-in.-thick base of the soil container and, therefore, negligible. Bending strains were kept to tolerable limits by selecting a lower-assembly-container-plate thickness that would provide the bending resistance required to accomplish this. Consequently, it was anticipated that the equipment deformations would not exceed 50 μin., even under the worst conditions (1000-psi pressure, with the device assembled in the auxiliary configuration).

The purpose of the first equipment-compressibility test, which was conducted just as an actual test, with a 10-in.-diam, 1-in.-thick steel plate acting as the specimen, was to provide experimental data to support the design assumptions. Unfortunately, the results of the test clearly indicated that one or more factors had been overlooked. The recorded displacements at 1000 psi were approximately 15 mils, or 15,000 μin., 300 times the value anticipated. Furthermore, the recorded displacements were highly erratic. When the fluid chamber was first pressurized (at the beginning of the test), two of the four displacement transducers indicated negative displacements. Throughout the test, the displacements occurred in a series of sudden changes rather than as a continuous function of pressure. Also, when unloading was initiated, the displacements continued to increase before eventually decreasing.

Several hypotheses were proposed concerning the sources of the large equipment deformations and their erratic nature, and a series of tests was conducted to determine which, if any, of them were valid. The test details varied considerably. Some tests, like the first, were

conducted just as an actual test, but with a rigid, steel specimen. Some were conducted without a specimen and with discs seated on or bonded to the base of the soil chamber. In other tests, the rods were threaded directly into holes in the base of the soil chamber specifically machined for this purpose. In some tests, the full flexible membrane was used, and the soil chamber was isolated from the fluid chamber; in some tests, the membrane was not used; in other tests, the membrane was used, but many holes were punched through it so the soil chamber would not be isolated from the fluid chamber. Although the soil container with the 1-in.-thick soil chamber was used in most of the tests (because the effect of equipment compressibility is 2-1/2 times more important for a test on a 1-in.-thick specimen than it is for a test on a 2-1/2-in.-thick specimen), the other soil container was used frequently.

The test series, or equipment-compressibility study, proved to be rather extensive, and only the most important findings are summarized below. The data referenced are presented in Appendix B. The data for nearly all tests were recorded continuously, and readings were taken as required for definition. (Smooth curves were drawn through the points, except where a sudden change was actually known to have occurred.)

Core System and Coil Support. It has been stated that the equipment components whose deformations contribute to an error in the specimen-deformation measurement are those which lie in the load-support system between the displacement sensor and the reference relative to which the displacement is made (Section 2.2). In the WES device, the contributing components are those which lie in the load-support system between the LVDT core and the LVDT coils--the base of the soil container, the

lower assembly container plate, the fluid container, the membrane between the soil container and fluid container, the core system, and the coil support system.

In the design of the WES device, as stated above, only the soil container and lower assembly container plate were considered. Contributions from the fluid container and the membrane were neglected, since these contributing components are not subjected to appreciable vertical stress changes during a test. Contributions from the core system and coil support system were inadvertently overlooked. In the case of the coil support system, the oversight was not too serious, since the only vertical loading experienced by the coil support system results from inertia in tests of very short duration, and it can be shown that the equipment compressibility from this source is probably negligible (see Section A.7). In the case of the core system, however, the oversight was found to be significant, particularly since it had been decided (as a result of other considerations) to use relatively flexible, Plexiglas core rods.

The contributions of the 10-in.-long Plexiglas core rod to the equipment deformations observed was estimated as 10 mils at a pressure level of 1000 psi. (A Young's Modulus of 400 ksi and a Poisson's Ratio of 0.3 were assumed for the computation.) This was substantially verified by the experimental data. After the Plexiglas core rods had been replaced by stainless-steel rods, the equipment deformations were found to vary from 2 to 5 mils, a decrease of approximately 10 mils from the 15 mils observed during the tests with the Plexiglas rods.

Although it was possible to reduce the compressibility of the core rod by changing from Plexiglas to stainless-steel rods, it was not

possible to reduce the compressibility from this source to the 0.05-mil level considered to be desirable (Section A.5), since the deformation of the stainless-steel rod at 1000 psi is approximately 0.13 mil. Nevertheless, since the nature of the deformation is such that it can readily be predetermined, and since the magnitude of the deformation is well within the tolerable (if not desirable) range, there was no consideration given to redesigning the specimen-deformation measurement.

Pneumatic Loading. It is evident from the results of the equipment-compressibility study that a purely pneumatic load-application system can be an important source of equipment deformations, even for fairly long duration loadings (see Section 4.3).

Planeness of Mating Surfaces. During many of the tests in the equipment-compressibility study, there were two pairs of mating surfaces in the device through which the total load was transmitted--the soil container-lower assembly container plate interface and the steel specimen-soil container interface. Although the machining tolerance specified for the various surfaces was 1 mil, precision measurements made during the equipment-compressibility study (with an 0.1-mil dial indicator) indicated that the tolerance had not been met. (Since precision measurements had not been made following fabrication, it was also possible that the tolerance had been met, and the deviations from a plane surface resulted from use.) Points on the base of the soil container with the 1-in.-deep chamber were found to deviate from a plane surface by as much as 4.5 mils (Fig. 42); the planeness of the other surfaces was somewhat better.

The mismatch at each of the two interfaces contributed significantly to the equipment deformations observed. The initial negative values

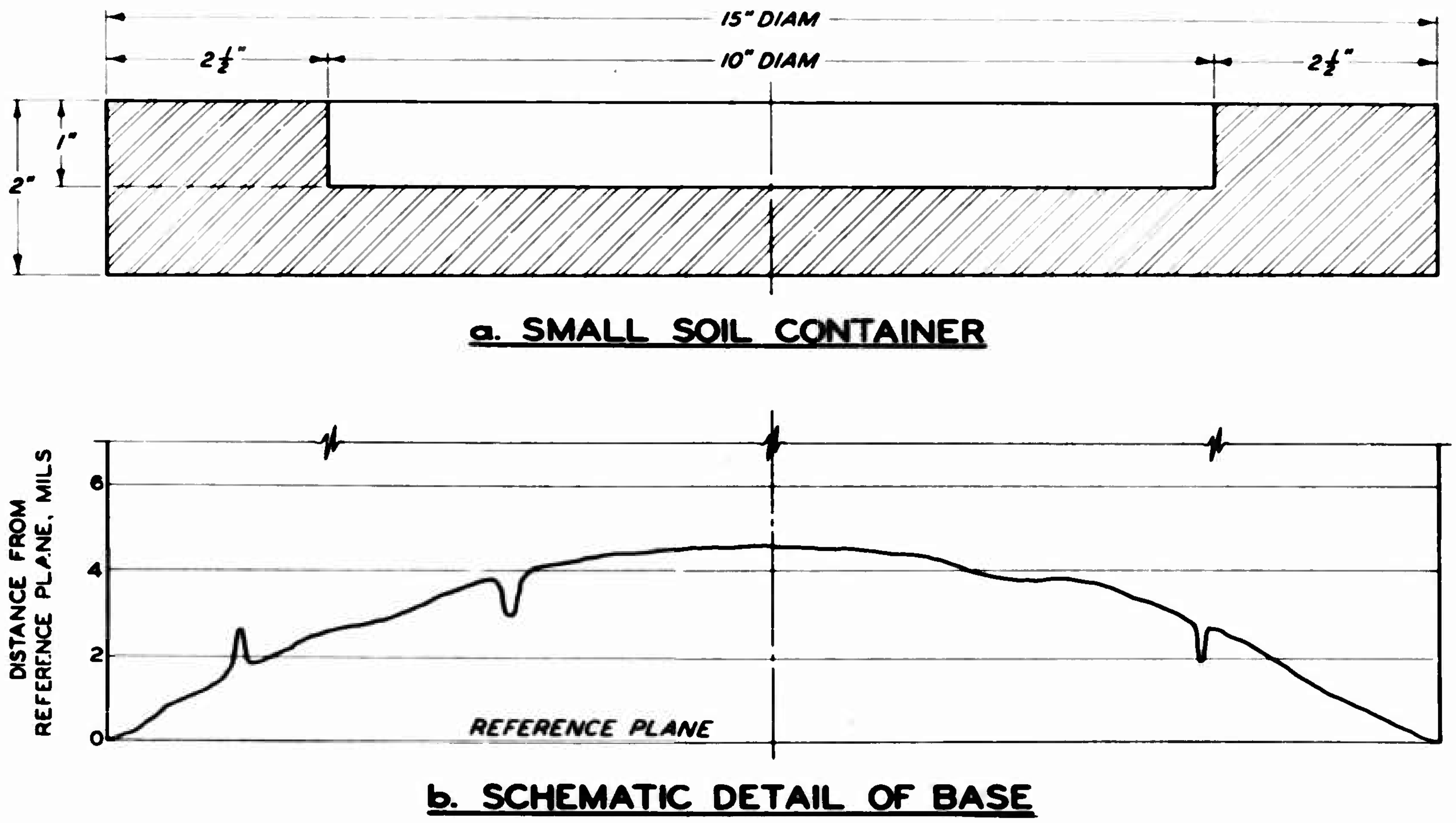


Fig. 42. Schematic drawing of soil container showing deviations from plane surface at base.

of deformation were found to stem from the mismatch at the steel specimen-soil container interface, which had apparently resulted in tilting of the steel specimen. After the bottom surface of the specimen had been mated to the base of the 1-in.-deep soil chamber by lapping, the negative displacements were no longer observed.

Since the improved fit between the steel specimen and the soil container resulted in the elimination of negative displacements, it was assumed that the fit was satisfactory in all respects. This did not prove to be the case, however, as can readily be seen by comparing the results of Test Nos. 47 and 51 in the equipment-compressibility study (Figs. 113 and 114). Both tests were conducted with the device assembled in the principal configuration. In Test No. 47, the steel specimen was not used, and the LVDT core rod was threaded into the base of the soil container; in Test No. 51, which was conducted as an actual test, the steel specimen was used. Although the difference in compressibility could have resulted from other differences between the two tests (e.g., both the core disc and the flexible membrane were used in Test No. 51 but not in Test No. 47), it was not considered to be likely. This was later verified by the results of Test No. 56, which differed from Test No. 51 in only one respect. In Test No. 56, the soil chamber was carefully filled with water before the steel specimen was placed inside it, whereas, in Test No. 51 (as in all tests prior to it, in which the steel specimen was used), the steel specimen was simply inserted into a dry soil chamber. In comparing the results of Test Nos. 51 and 56 (Figs. 114 and 115), it is clear that the difference in compressibility between these two tests stemmed from a mismatch at the steel specimen-soil container interface. In Test No. 56, the mismatch was not

effective, because the mismatched volume had been filled prior to the test. (Note the similarity in the results of Test Nos. 47 and 56.) In order to avoid any additional difficulties resulting from this interface mismatch, the use of the steel specimen was discontinued after Test No. 56.

After the precision measurements mentioned above had shown that there was a significant mismatch at the soil container-lower assembly container plate interface, the bottom surface of the small soil container and the top surface of the lower assembly container plate were repeatedly machined until the originally specified tolerance of 1 mil was met. The results of Test Nos. 22 and 23, which were conducted (without the steel specimen) before and after the remachining of the two surfaces was undertaken, indicate the degree of improvement.

Although it was recognized that the planeness of the mating surfaces could be further improved either by additional remachining or by hand lapping, it was considered to be more desirable to eliminate the interface entirely. The one-time cost of a single-piece soil container-lower assembly container plate was thought to be preferable to the initial cost and subsequent maintenance costs (whenever one or more of the surfaces became damaged) of precision machining for the separate pieces. It was also recognized that if separate pieces were used, there would always be the possibility of equipment-compressibility errors resulting from the inclusion and subsequent crushing of some foreign matter (such as a sand grain) between the two surfaces. Consequently, it was decided to replace the two soil containers and the lower assembly container plate with two single-piece soil container-lower assembly container plates.

<u>Fluid Container-Soil Container Separation</u>. It is clear that

in each of the two test configurations, there is a tendency for the fluid container to be raised off the soil container by the induced pressure (up to the O-ring) at the fluid container-soil container interface. In the design of the device, it was intended that the assembly bolts would prevent only gross motions of the fluid container. Consequently, a method was devised by which the fluid container would always tend to remain clamped to the soil container, even as the assembly bolts stretched under load. The inside diameter of the O-ring at the top of the fluid container was designed to be larger than the inside diameter of the O-ring groove at the bottom of the fluid container so that there would be a net downward force on the fluid container at all times (Section 3.6).

In the principal configuration, the fluid container appeared to remain clamped to the soil container as anticipated. However, there was ample evidence that the fluid container was being lifted slightly under pressure in the auxiliary configuration. The results of Test Nos. 25 and 28 (Figs. 110 and 111) provide a good example. The two tests were conducted under the same conditions, except that in Test No. 25 the coil support plate was supported independently (i.e., off the device), and in Test No. 28 it was supported as usual (Fig. 17). The additional 1.2 mils of deformation recorded for Test No. 28 reflect the upward displacement of the coils relative to the core that took place during that test. The upward displacement of the coils resulted from the lifting of the fluid container off the soil container.

That the fluid container could be lifted off the soil container, in spite of the precaution taken to prevent this, indicated that some driving force had been overlooked. The only driving force that could

be responsible is the O-ring at the bottom of the fluid container. As the pressure in the fluid chamber is increased, the lateral fluid pressure tending to push this O-ring outward into the fluid container-soil container interface is increased as well. In the principal equipment configuration, the stress change in--and, consequently, the deformation of--the assembly bolts is small, so the O-ring is prevented from being pushed into the interface and raising the fluid container. In the auxiliary equipment configuration, on the other hand, the stress change in the assembly bolts is large. Consequently, the deformation of the bolts is large, and there is less resistance to the O-ring's being squeezed into the interface. It should be noted that the upward motion of the fluid container is only approximately 1.2 mils at 1000 psi; at the same pressure level, the extension of the 1-in.-diam bolts is computed to be somewhat more than 3 mils for initially unstressed bolts, so the explanation proposed appears to be feasible.

If the explanation proposed above is correct, it follows that a test conducted under the same conditions as Test No. 28, but with a greater torque applied to the assembly bolts, would result in less lifting of the fluid container and less measured compressibility than in Test No. 28. Test No. 30 is such a test; the torque used for nearly all tests prior to Test No. 30 was 100 ft-lb, and the torque used for Test No. 30 was 300 ft-lb. The results of Test No. 30 (Fig. 112) not only verified that the equipment compressibility is inversely proportional to the magnitude of the torque applied to the assembly bolts, as hypothesized, but also suggested that a torque of 300 ft-lb applied to the assembly bolts results in sufficient initial tension in these bolts to resist the O-ring from

squeezing into the fluid container-soil container interface, even at a pressure of 1000 psi. (Compare the results of Test Nos. 25 and 30.)

The simplest method for eliminating that portion of the equipment-compressibility error which results from lifting of the fluid container off the soil container in the auxiliary configuration would have been to adopt 300 ft-lb as the standard torque to be used in tightening the assembly bolts. Unfortunately, this could not be done conveniently. It was found that when a torque of 300 ft-lb was applied to the assembly bolts, the glue connecting the flexible membrane to the fluid container failed. Because of the time required for the preparation of a new membrane, it is not feasible to prepare one for each test. There was also some difficulty involved in obtaining a reaction for the 300-ft-lb torque. Note that the nuts for the assembly bolts are contained within the lower assembly container plate (Fig. 17). For a torque of 100 ft-lb, the friction between the lower assembly container plate and the board on which it is placed during assembly is sufficient to resist rotation of the device as a whole. For a torque of 300 ft-lb, a reaction is required to prevent the entire device from rotating as the torque is applied.

It was decided to retain the 100-ft-lb torque, and to prevent the upward movement of the fluid container by redesigning the load-support system for the auxiliary equipment configuration so that it would be similar to that of the principal equipment configuration. This was done by dividing the load-support system into two parts (Fig. 18), one part--the two assembly container plates and every other assembly bolt--for the induced load, and the other part--the two reaction frame plates and six columns--for the applied load. With the device assembled in the modified

configuration, the increase in fluid-chamber pressure does not result in a large stress change in the assembly bolts, so the O-ring at the bottom of the fluid container is prevented from being squeezed into the interface and raising the fluid container. Experimental verification was provided by the results of all the tests conducted with the device assembled in the modified auxiliary configuration (e.g., Test No. 66, Fig. 116).

<u>Current Status</u>. The relationship between equipment compressibility and pressure for the device assembled in the modified test configurations (Figs. 15 and 18) depends on the test duration and on the particular soil container-lower assembly container plate used in the assembly. In nearly all cases, the relationship is approximately linear, although some significant departures from a straight-line relationship have been observed, particularly during the unloading portions of short-duration tests. When the soil container-lower assembly container plate with the 1-in.-deep chamber is used, the equipment compressibility is approximately 0.5 μin. per [illegible]ing long-duration tests and approximately 0.75 μin. per psi during short-duration tests (Figs. 116-118). These values, which were obtained by connecting the peak pressure-compressibility point and zero by a straight line, were found to be repeatable to 0.03 mil (when evaluated at peak pressure). Corresponding values for tests in which the other soil container-lower assembly container plate is used are approximately 0.33 and 0.6 μin. per psi.

It is fortunate that the relationship between equipment compressibility and pressure for a particular test setup and duration range is fairly repeatable (so that it can be precalibrated), because the magnitude of the compressibility observed cannot readily be explained. The

compressibility of the core system is approximately 0.13 μin. per psi, and the compressibility of the soil container-lower assembly container plate (combining bending and shear) probably does not exceed 0.1 μin. per psi. The remainder of the observed compressibility may stem from a variety of sources (e.g., mismatch at LVDT core disc-soil chamber interface, separation of fluid and soil containers, etc.), none of which can be evaluated conveniently.

There was little difference between the magnitude of the equipment deformations observed during a long-duration test and the magnitude of the equipment deformations observed during a short-duration test, conducted under otherwise similar conditions, throughout the equipment-compressibility study. Although the difference observed for tests conducted near the end of the study is approximately 45 percent (Test Nos. 70 and 71, Figs. 117 and 118), it is important to note that the corresponding difference in magnitude of the equipment deformations is only 0.07 mil at 300 psi (the peak pressure obtainable for a short-duration test). This difference is probably real (rather than a result of a frequency-response limitation in the measurement system--see Section 4.5) and may result from a small difference in the path of load transfer in the load-support system during the two types of tests.

It appears, therefore, that the equipment-compressibility error will be less than or equal to the 1 percent specified for all specimens of interest, provided that the specimen-deformation measurement is corrected for equipment compressibility as required (see Section A.5). A single determination of the relationship between equipment compressibility and pressure, for each soil container-lower assembly container plate and for

each loading- (and unloading-) duration range, should be sufficient for nearly all test conditions of interest; however, even if this does not prove to be the case, and the magnitude of equipment compressibility must be determined for each set of test conditions, such a determination can probably be made conveniently without the necessity for a separate calibration test for each test conducted (see final portion of Section 4.5).

4.5 Measurement System

4.5.1 Amplifier-Recorder System

The entire measurement system used in conjunction with the WES one-dimensional compression device is shown schematically in Fig. 30. A photograph of the instrumentation room where the amplifier-recorder system is installed is shown in Fig. 29.

In the schematic drawing of the entire measurement system, each of the carrier amplifier units is depicted as a source of voltage amplification for four instrumentation channels. This was done for simplicity. It is desirable, before proceeding with a review of the evaluation program pertaining to the amplifier-recorder system, to consider briefly the actual many-faceted role of the amplifier unit used.

A schematic drawing of a single instrumentation channel, representing any of the channels in the measurement system with the exception of the one associated with the piezoelectric pressure transducer, is shown in Fig. 43. During operation (i.e., when there is a nonzero mechanical signal sent to the transducer), the 3-kc carrier voltage (5 volts) generated by the oscillator in the amplifier unit is modulated by the transducer and returned to the amplifier unit. The modulated return or output signal is

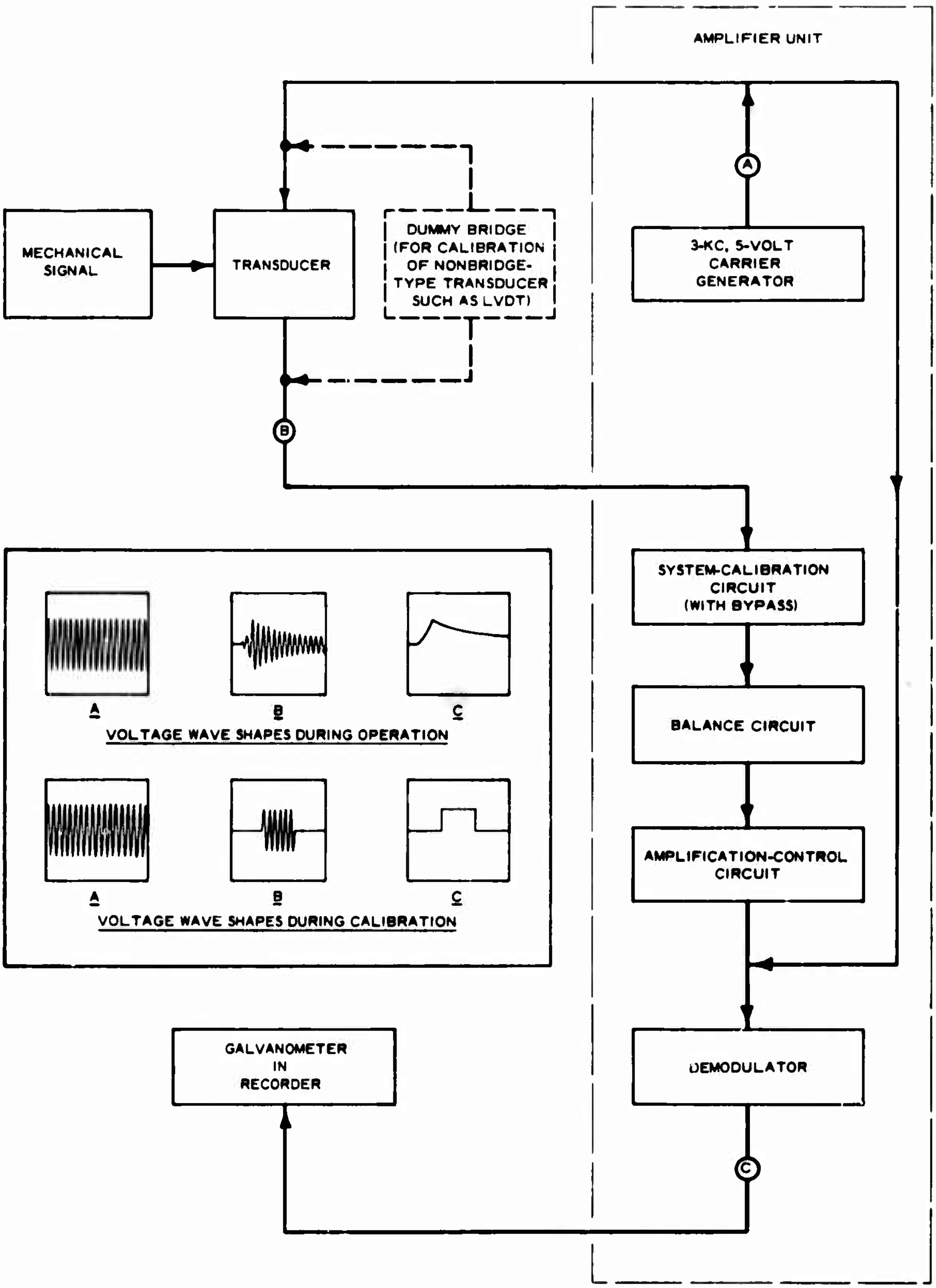
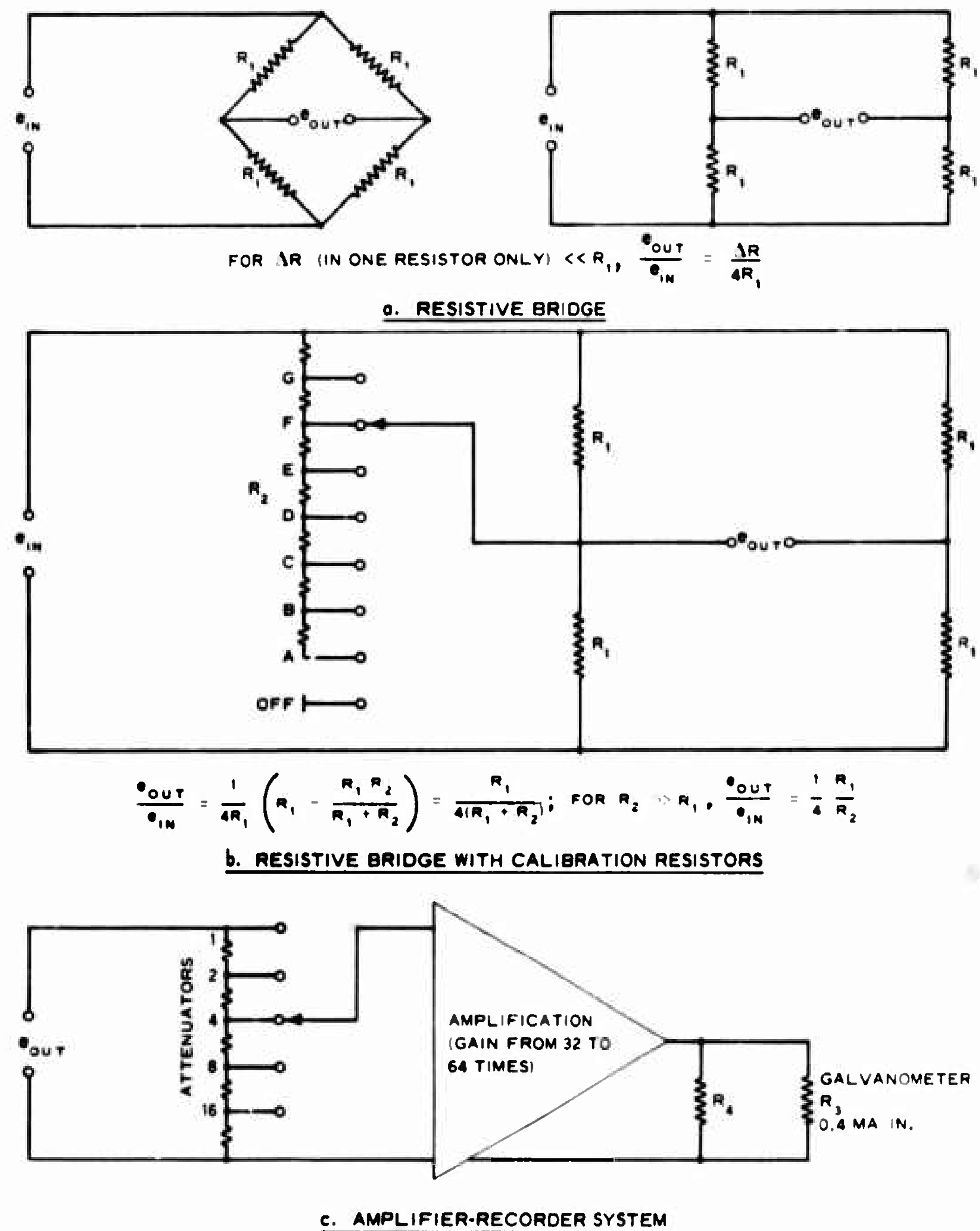


Fig. 43. Schematic drawing showing details of typical instrumentation channel.

then amplified by the amplification-control circuit to yield the desired galvanometer excursion. (The amplification settings are adjusted prior to the test to accomplish this.) After the return signal has been amplified, it is demodulated in the amplifier unit and sent to the recorder, where it is used to drive the galvanometer. During system calibration (i.e., prior to and/or after each test or transducer calibration, when the amplitude of the mechanical input signal is zero), the 3-kc carrier voltage is modulated by the calibration circuit-bridge (transducer bridge or dummy bridge) combination and returned to the amplifier unit. The modulated return or output signal is then treated as described above for actual operation. In all cases, the balance circuit is used to set the initial output voltage at zero, since in reality small imperfections in the resistor values give rise to a small output voltage even when the mechanical input signal is zero.

For convenience in transducer calibration and data reduction, the typical instrumentation channel is designed to be linear. After the transducer converts a mechanical input signal into a proportional electrical output signal in the form of voltage (as, for example, in the simple resistive-bridge circuit shown in Fig. 44), the amplifier unit converts this output voltage signal into a proportional output current signal (Fig. 44c). The output current drives a galvanometer (in the recorder), which is designed to rotate by an amount proportional to the current through it. As the galvanometer rotates, the light beam which it directs onto a light-sensitive paper is deflected, and a permanent record of galvanometer excursion is obtained. Because the angle through which the galvanometer rotates is very small, the linear excursion recorded on the



e_{IN} = 5 V.
R_1 = 120 Ω OR 350 Ω
R_3 = 69 Ω FOR 7-364
R_4 = 220 Ω FOR 7-364

R_2 =
5,000 Ω FOR STEP G
10,000 Ω FOR STEP F
20,000 Ω FOR STEP E
40,000 Ω FOR STEP D
80,000 Ω FOR STEP C
160,000 Ω FOR STEP B
320,000 Ω FOR STEP A

d. TYPICAL VALUES

Fig. 44. Schematic circuit drawings of several aspects of typical instrumentation channel.

light-sensitive paper is proportional to the actual angular excursion and hence to the input mechanical signal.

The amplification-control circuit in the amplifier unit affords the opportunity of using a single transducer unit for several different ranges of mechanical input. The amplifier unit must provide 1.6 milliamps of current to--or 110 millivolts across--the Type 7-364 galvanometer used, in order to drive the galvanometer 4 in., as desired (see Section 3.6), at peak output voltage (Fig. 44c). Since this can be done for any peak output voltage (from the transducer) from 1.7 to 55 millivolts (approximately), various ranges of mechanical input signals to a given transducer unit can be recorded accurately. (The accuracy is limited only by the accuracy of the transduction in the various ranges.)

Basically, the function of the system-calibration circuit is to provide an indication of the degree of amplification provided by the amplifier unit at the gain setting selected. (Although the attenuator settings are marked, the gain settings are not.) After the output voltage has been brought to zero by proper adjustment of the balancing circuit, the system-calibration circuit is activated, and a set of calibration resistors is introduced in parallel with one of the elements in the strain-gage bridge (Fig. 44b). An output voltage is generated in accordance with the equation shown, and the corresponding galvanometer excursion, or step, is recorded. If it is desired to conduct another test at some later time with the same amount of amplification, the system-calibration circuit can be activated and the attenuator and gain settings adjusted until this same galvanometer excursion is obtained.

The system-calibration circuit can be used in the manner

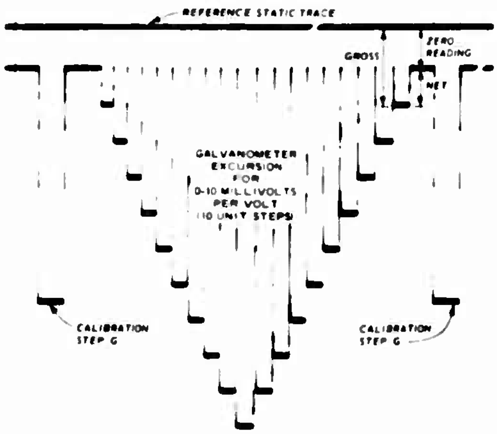
described for any instrumentation channel, whatever the relationship between the mechanical input signal and galvanometer excursion. It is important to note, however, that the system-calibration circuit is a far more versatile tool when used in conjunction with a linear instrumentation channel. In this situation, the calibration step not only provides a galvanometer excursion which is indicative of the degree of amplification selected, but it also provides a galvanometer excursion which is proportional to the degree of amplification selected. Since both the system-calibration circuit and the transducer circuit are linear and since both lead to the same linear amplifier-recorder circuit, the calibration step can be considered to represent or simulate a given mechanical input signal, in that both will provide the same galvanometer excursion for any degree of amplification provided. Thus, once the relationship between the mechanical input signal and the galvanometer excursion has been determined for one degree of amplification--a procedure referred to herein as transducer calibration--any relationship (or scale) desired thereafter can be preset without the need for another transducer calibration. If, for example, it has been determined that a particular pressure transducer causes a galvanometer excursion of 4 in. when the pressure is 1000 psi and when the amplification is such that Calibration Step F causes a galvanometer excursion of 2 in., then the mechanical-input value of Step F can be considered to be 500 psi; if a scale of 4 in. = 500 psi is desired, the attenuator and gain settings are simply adjusted until Step F = 4 in.

It should be noted that two sets of cables were used to connect the various transducers in the laboratory to the rest of the amplifier-recorder system in the instrumentation room. One set was used for

short-duration tests conducted under the Dynapak loader (Fig. 38) with the device assembled in the principal configuration, and the other set was used for long-duration tests conducted in a different part of the laboratory (Fig. 37) with the device assembled in the auxiliary configuration. Except for the cables, however, the same amplifier-recorder system was available for all types of tests.

Static Linearity. The relationship between output voltage and galvanometer excursion was determined statically for each of the channels in the measurement system, and was found to be linear to ±1 percent or better for all but one of the channels. The source of nonlinearity in that channel was found to be the galvanometer, and it was replaced by another unit. With the new galvanometer in place, the relationship between output voltage and galvanometer excursion was found to be linear to ±0.75 percent.

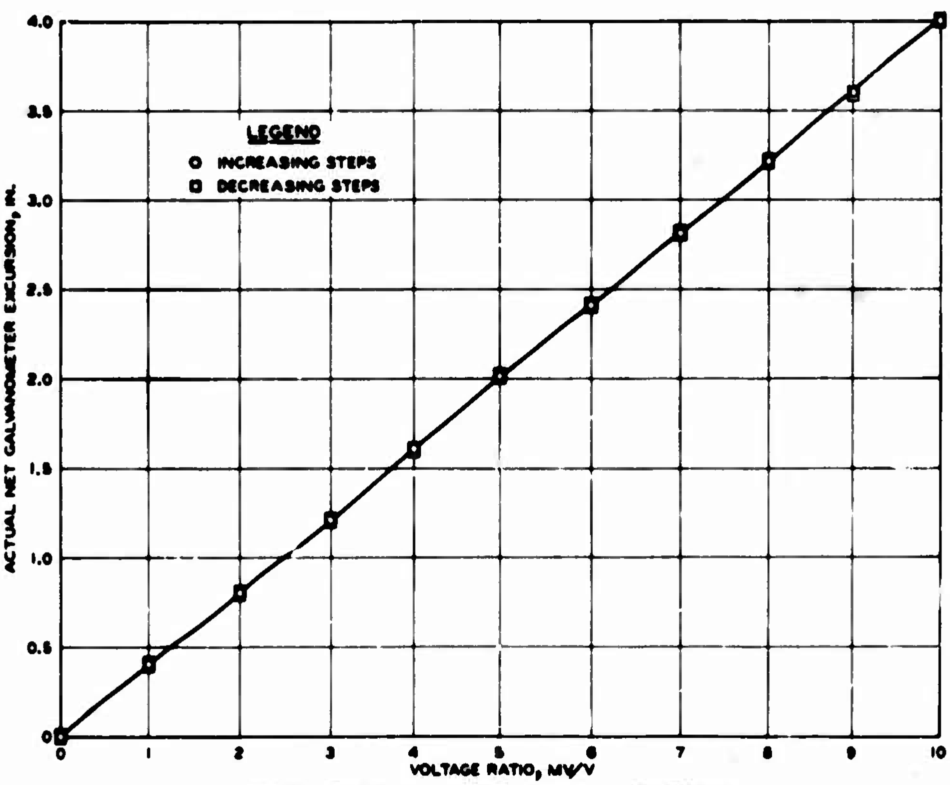
The relationship between output voltage and galvanometer excursion was determined by a standard technique. As each channel in the measurement system was evaluated, the transducer for that channel was replaced by a precision calibrator specifically designed for the purpose (Baldwin-Lima-Hamilton Model 625); the rest of the circuit (Fig. 43) remained unchanged. With the range setting on the precision calibrator at 0 to 10 millivolts per volt (arbitrarily selected) and with the switch setting at 0, the system was balanced, and the zero position of the galvanometer (corresponding to an output voltage of zero) was recorded. The switch setting was then changed from 0 to 10 in unit increments, thus inducing output-to-input voltage ratios of precisely 1 to 10 in unit increments. (The input voltage remained constant at a value of approximately 5 volts.) The galvanometer excursion corresponding to each of the voltage ratios was



a. OSCILLOGRAPH PHOTOGRAPH

STATIC LINEARITY DETERMINATION AMPLIFIER-RECORDER SYSTEM CHANNEL 1	VOLTAGE RATIO MV/V	NET GALVANOMETER EXCURSION, IN.	
		ACTUAL	NORMALIZED
	0	0.00	
	1	0.41	
	2	0.82	
	3	1.23	
	4	1.64	
	5	2.03	
	6	2.42	
	7	2.82	
	8	3.21	
	9	3.60	
	10	4.00	
	9	3.60	
	8	3.21	
	7	2.82	
	6	2.42	
	5	2.03	
	4	1.63	
	3	1.23	
	2	0.82	
	1	0.41	
	0	0.00	
	B	0.06	
	C	0.17	
	D	0.34	
	E	0.67	
	F	1.32	
	G	2.60	
CALIBRATION TEST NUMBER	1		
BEST LINEAR RELATION FOR DATA	4.02" = 10 MV/V		
MAXIMUM DEVIATION FROM BEST LINEAR RELATION	0.01 INCH		
MECHANICAL-INPUT VALUES FOR CALIBRATION STEPS	G = 6.67 MV/V		
NORMALIZED RELATION			

b. DATA TABULATION



c. DATA PLOT (ILLUSTRATING LINEARITY)

Fig. 45. Results of typical calibration test for amplifier-recorder system.

recorded. The procedure was then repeated in reverse, as the switch setting was returned to 0 in unit increments.

The results of a typical evaluation test are shown in Fig. 45, where the maximum deviation from the best straight line through the points is approximately ± 0.75 percent. Differences between data points obtained for the increasing steps and those obtained for the decreasing steps are insignificant. (The mechanical-input value of Step G, for the precision calibrator, was found to be 6.47 millivolts per volt for this particular channel.)

Repeatability. Linearity of the amplifier-recorder system is of secondary importance when compared with repeatability. Although a unique, nonlinear relationship between output voltage and galvanometer excursion (for a given degree of amplification) is inconvenient to work with, it is not limited in accuracy, as is a linear relationship that is not unique.

Some time after the relationship between output voltage and galvanometer excursion had been determined for each of the channels in the measurement system, all were checked for repeatability, and were found to be repeatable to better than 1 percent (with the first test arbitrarily selected as the reference).

The results of a typical repeatability check are shown in Fig. 46, where the repeatability in two determinations was found to be approximately 0.4 percent (as reflected by the mechanical-input values determined for Step G).

Drift. Several methods were used to determine the amount of drift--change in galvanometer excursion with time, without change in

amplification settings--in the amplifier-recorder system. In all cases, the drift was found to be less than 2 percent of full-scale galvanometer excursion, i.e., less than 0.08 in.

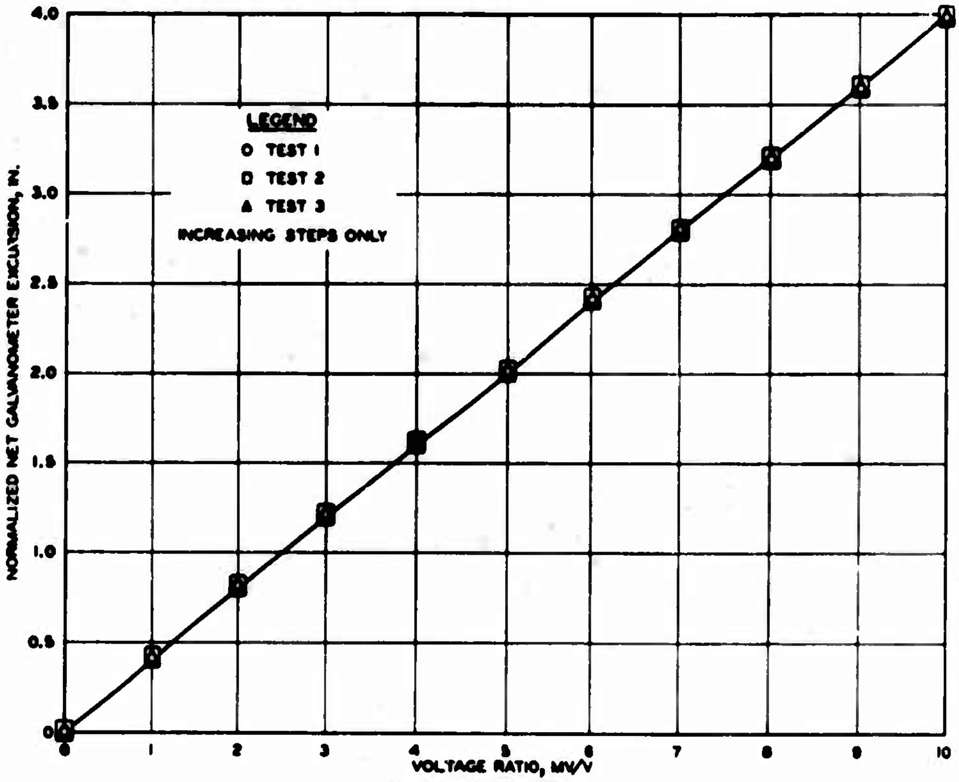
Most of the information concerning drift was determined by comparing the galvanometer excursions for the calibration steps that were obtained prior to each test (including the equipment-compressibility tests, the transducer calibration tests, and the actual tests) with those that were obtained after the test. The difference was nearly always found to be less than 1 percent of the actual galvanometer excursion. In a very few cases, all associated with an LVDT channel, differences as great as 2.2 percent of the actual excursion were found.

On two occasions, the various instrumentation channels in the measurement system were evaluated for drift under more severe conditions. At the end of the day, the channels were balanced, the galvanometer excursions for the calibration steps were recorded, and the electric power was turned off for the night. The following morning, after the equipment had been given an opportunity to warm up, the galvanometer excursions for the calibration steps were again recorded. In all cases, the overnight change in galvanometer excursion was found to be less than or equal to 1.25 percent of the actual excursion.

Since static traces on the oscillogram were used as the references relative to which the galvanometer excursions were measured (see, for example, Fig. 45), it was thought to be desirable to determine the drift associated with static traces as well. (A static trace is made by a beam of light reflected from an open-circuited galvanometer.) Twenty tests were selected at random, and the distances separating the three

STATIC LINEARITY DETERMINATION AMPLIFIER-RECORDER SYSTEM CHANNEL 1 REPEATABILITY CHECK	VOLTAGE RATIO, MV/V	NET GALVANOMETER EXCURSION, IN.		VOLTAGE RATIO, MV/V	NET GALVANOMETER EXCURSION, IN.		VOLTAGE RATIO, MV/V	NET GALVANOMETER EXCURSION, IN.	
		ACTUAL	NORMALIZED		ACTUAL	NORMALIZED		ACTUAL	NORMALIZED
	0	0.00	0.00	0	0.00	0.00	0	0.00	0.00
	1	0.41	0.41	1	0.41	0.41	1	0.41	[illegible]
	2	0.82	0.82	2	0.82	0.81	2	0.82	0.81
	3	1.22	1.22	3	1.22	1.21	3	1.22	1.21
	4	1.60	1.60	4	1.60	1.61	4	1.62	1.61
	5	2.00	2.00	5	2.00	2.01	5	2.02	2.01
	6	2.42	2.41	6	2.40	2.41	6	2.42	2.41
	7	2.82	2.81	7	2.81	2.80	7	2.82	2.80
	8	3.21	3.19	8	3.22	3.19	8	3.22	3.20
	9	3.60	3.60	9	3.63	3.60	9	3.63	3.60
	10	4.00	4.00	10	4.00	4.00	10	4.02	4.00
	9	3.60	3.57	9	3.60	3.60	9	3.63	3.60
	8	3.21	3.19	8	3.22	3.19	8	3.22	3.19
	7	2.82	2.81	7	2.82	2.80	7	2.82	2.80
	6	2.42	2.41	6	2.40	2.41	6	2.42	2.41
	5	2.00	2.00	5	2.00	2.01	5	2.02	2.01
	4	1.60	1.60	4	1.60	1.61	4	1.62	1.61
	3	1.20	1.20	3	1.20	1.20	3	1.22	1.21
	2	0.80	0.80	2	0.82	0.81	2	0.82	0.82
	1	0.41	0.41	1	0.41	0.41	1	0.41	0.41
	0	0.00	0.00	0	0.00	0.00	0	0.00	0.00
	[illegible]	[illegible]	[illegible]						
	[illegible]	0.161	[illegible]						
	[illegible]	[illegible]	[illegible]						
	[illegible]	0.670	0.667						
	[illegible]	1.33	1.33						
	5	2.00	2.00	5	2.01	2.00	5	2.01	2.00
CALIBRATION TEST NUMBER	1			2			3		
BEST LINEAR RELATION FOR DATA	4.00" = 10 MV/V			4.00" = 10 MV/V			4.00" = 10 MV/V		
MAXIMUM DEVIATION FROM BEST LINEAR RELATION	0.03 INCH			0.02 INCH			0.02 INCH		
MECHANICAL-INPUT VALUES FOR CALIBRATION STEPS	6 = 6.47 MV/V			6 = 6.46 MV/V			6 = 6.46 MV/V		
NORMALIZED RELATION	4.00" = 10 MV/V			4.00" = 10 MV/V			4.00" = 10 MV/V		

a. DATA TABULATION



b. DATA PLOT

Fig. 46. Results of typical repeatability check on calibration of amplifier-recorder system.

static traces on the oscillogram for each of these tests was measured. Measurements were made (with a 50 scale) at one end of each oscillogram (representing the beginning of a test) on one day, and at the other end (representing the end of a test) on another day, so there would be no prejudice in the readings obtained. In no case did the distance separating a pair of static traces at one end of the oscillogram differ from the corresponding distance at the other end of the oscillogram by more than one division on the 50 scale, or 0.02 in.

Clearly, drift in the amplifier-recorder system, with or without the calibration-control circuit activated, is not a significant factor with regard to accuracy. Since the average of the two galvanometer-excursion values obtained for each calibration step was used to determine the amplification or scale for the test, the error resulting from drift of the signal in the amplifier-recorder system never exceeded ± 1.1 percent, and was this great in only a very few cases.

Frequency Response. Since it was anticipated that the frequency range of the measured signals would be 0 to 80 cps (Section A.1), the frequency-response characteristics of the amplifier-recorder system were evaluated for a mechanical input frequency of 80 cps. During the evaluation, the transducer in the amplifier-recorder circuit was replaced by a simulation assembly consisting of a variable-frequency function generator (Wavetek Model 111), an analog computer (Electronic Associates, Inc., Model TR10), and a resistive bridge. The function generator provided an 80-cps electrical signal, simulating the desired 80-cps mechanical input signal. After the 3-kc carrier voltage (5 volts) was modulated by the 80-cps signal (1 volt) in the analog computer, it was returned to the

amplifier unit through the resistive bridge, which acted simply as a voltage reducer for the fairly high-amplitude return signal. When the return signal reached the amplifier, it was treated as any signal obtained during actual operation.

Data from the simulation test include three channels of information, all displayed on a single light-beam oscillograph record. The signal provided by the variable-frequency function generator was displayed on Channels 1 and 2. In both cases, the function generated was used to drive the galvanometer directly; the galvanometer for Channel 1 was a high-frequency unit (Type 7-363, with an undamped natural frequency of nearly 1700 cps), and the galvanometer for Channel 2 was the same type unit used in the measurement system (Type 7-364, 833 cps). Channel 3, representing the typical channel in the actual measurement system, contained the modulated return signal, which had passed through the regular amplifier-recorder system.

The results obtained agree very closely with those predicted (see Section A.4). The amplitude ratio, which was determined by relating the peak-to-peak amplitude of the signal on Channel 3 for an 80-cps input signal to the peak-to-peak amplitude of the signal on Channel 3 for a 1-cps input signal, was found to be 0.99. (In fact, the amplitude ratio for a 350-cps input signal was found to be 0.985; thereafter, the rate of decrease of amplitude ratio as a function of input frequency increased significantly.) The 80-cps signal on Channel 3 was found to lag the 80-cps on Channel 2 by 0.1 msec and the 80-cps signal on Channel 1 by 0.3 msec, indicating a time lag of approximately 0.1 msec in the galvanometer and a time lag of approximately 0.2 msec in the amplifier unit. The total time

lag in the amplifier-recorder system is probably 0.3 msec or less for all tests.

Resolution. The data from a one-dimensional compression test are displayed on a standard, 12-in.-wide sheet of direct-print, light sensitive paper, which is the oscillograph record. Sample oscillograph records for a short-duration test and for a long-duration test are presented in Figs. 47 and 48, respectively. (The figures were prepared by tracing the various curves and lines shown from the oscillograph records for Test Nos. A01P01 and A01A03 and then photographically reducing the tracings. Not shown in these figures are the calibration steps recorded before and after the tests, the zero traces recorded for all channels, and those portions of the oscillograph record for the short-duration test before and after the test during which the paper is accelerating and decelerating.)

The paper speed of the particular model oscillograph used can be adjusted from 0.16 to 160 in. per sec. Since a signal can generally be resolved fairly accurately to the nearest 0.02 in. (one division on a 50 scale), the time resolution available is nearly 0.1 msec.

When the peak value of the mechanical-input signal is known accurately in advance, the amplification or scale for the instrumentation channel which carries that signal is preset to provide 4 in. of galvanometer excursion for the peak value. Data from such channels can be resolved with an accuracy of ± 0.5 percent. When the peak value is not known in advance, it is estimated, and the scale is preset to provide 3 in. of galvanometer excursion for the peak value. Thus, if the peak value of a mechanical-input signal can be estimated within ± 30 percent, the data from

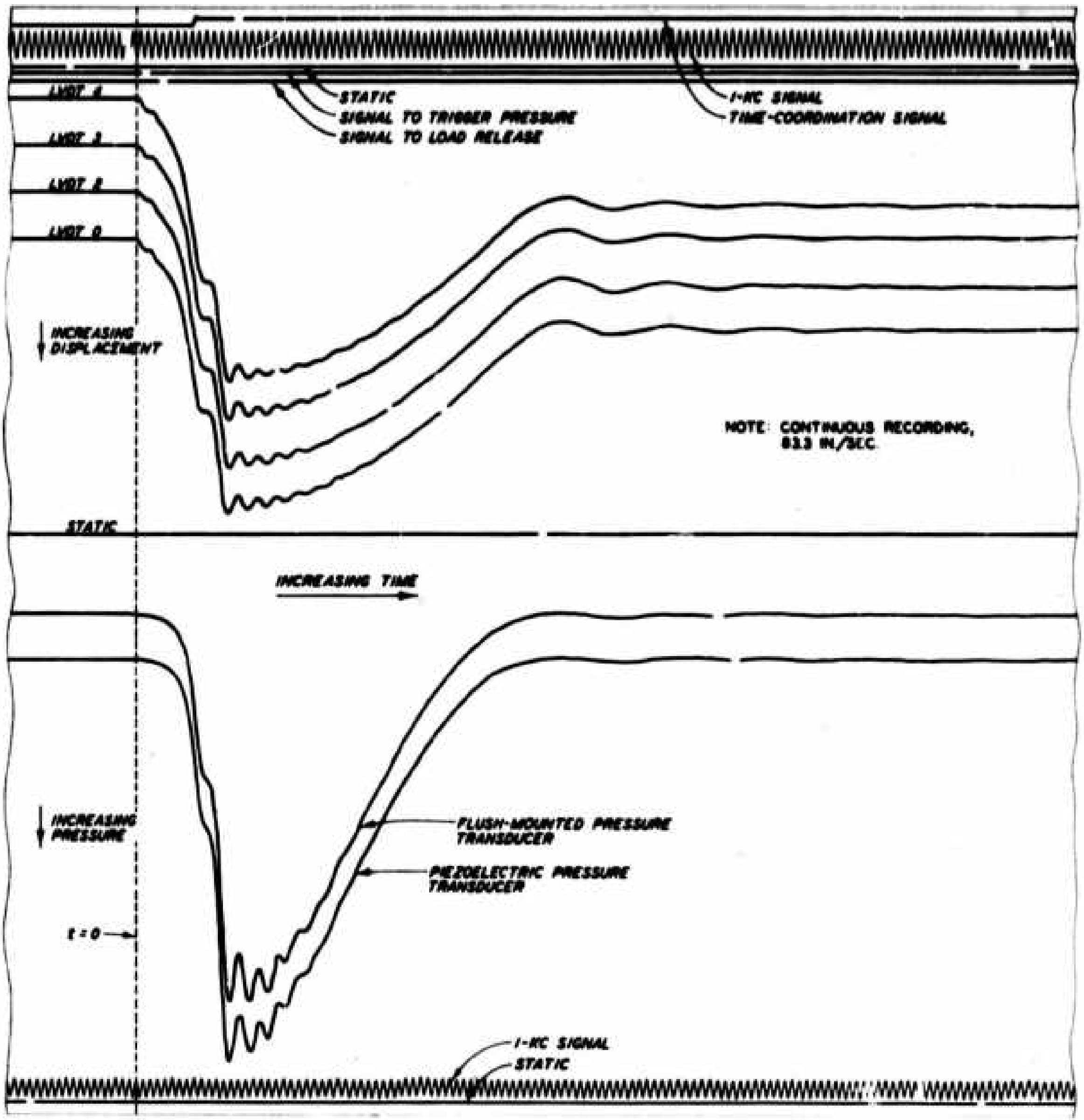


Fig. 47. Typical oscillograph record for short-duration test.

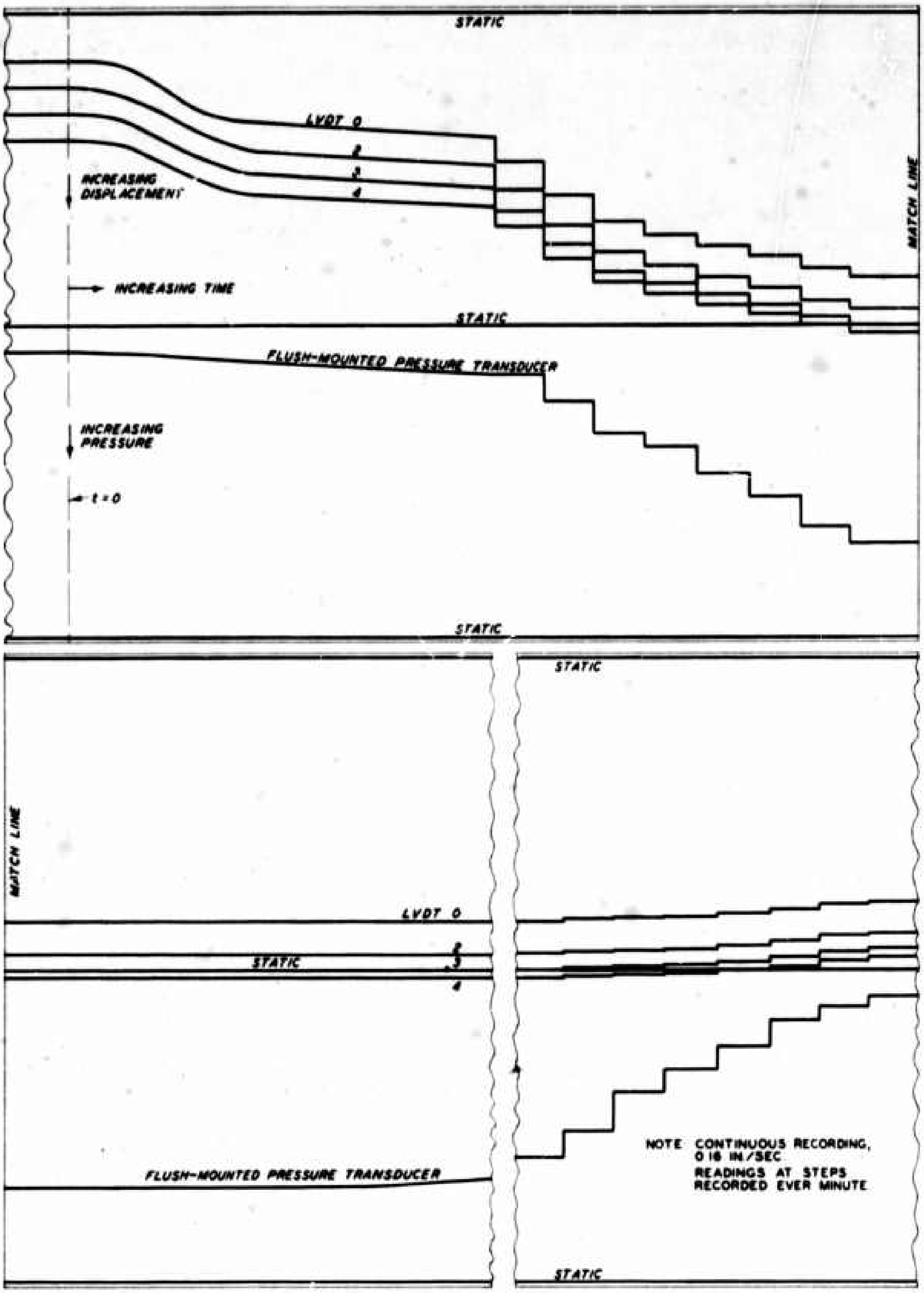


Fig. 48. Typical oscillograph record for long-duration test.

the channel which carries that signal can be resolved with an accuracy of ±1 percent, as specified.

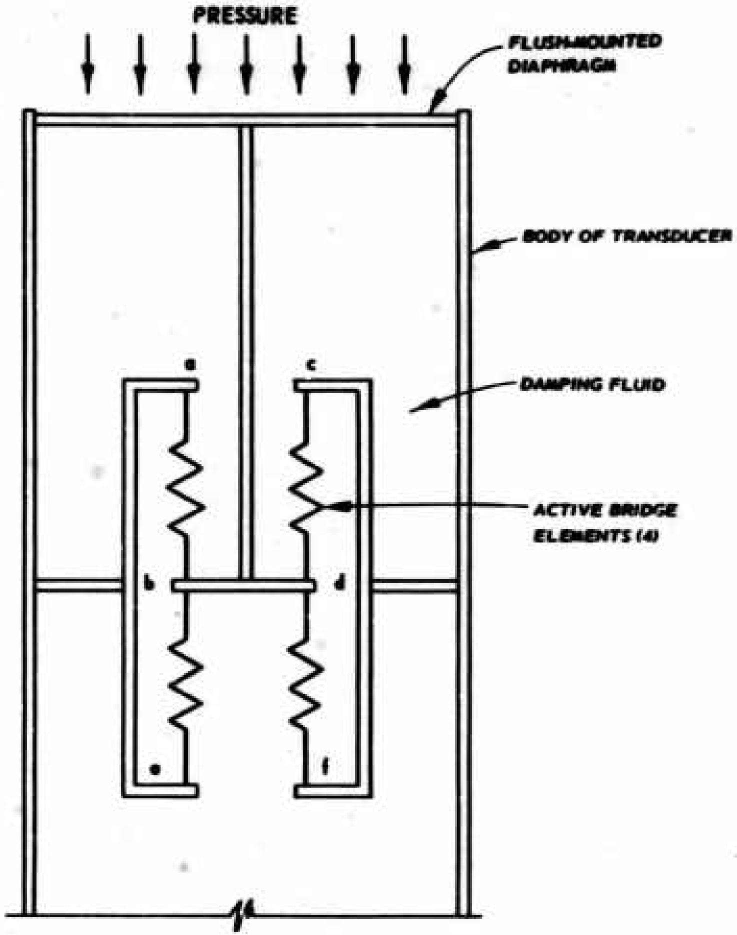
4.5.2 Key Measurement for Stress

A photograph of one of the flush-mounted pressure transducers used to determine the vertical stress in the specimen as a function of time is shown in Fig. 28. Schematic drawings depicting the mechanical and electrical operation of the transducer are shown in Fig. 49.

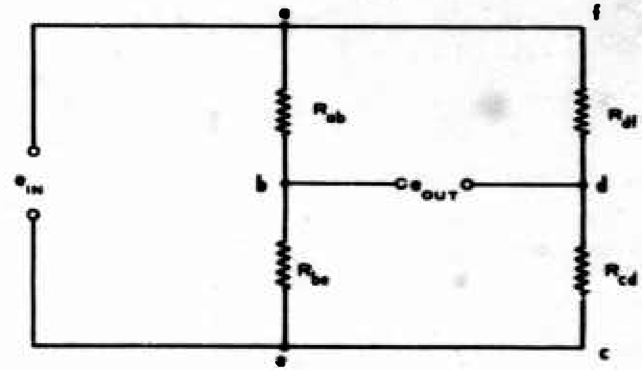
When the external pressure on the diaphragm is atmospheric, the resistance values of all four resistors are equal, and there is essentially no output voltage. (The small initial output voltage and the method used to bring it to zero were discussed in connection with the amplifier-recorder system.) As the external pressure is increased, the diaphragm bends, thus pushing the rod connected to its center inward. The motion of the rod changes the length of the four active strain-gage elements in the bridge, and, thereby, induces an output voltage in the circuit, in accordance with the relationship shown. Since the deflection of the center of the diaphragm is a linear function of external pressure, and since the output voltage is a linear function of the motion of the rod (which is equal to the deflection of the center of the diaphragm), the output voltage is a linear function of the external pressure.

Static Linearity. The relationship between external pressure on the diaphragm and galvanometer excursion was determined statically for each of the transducer units used, and was found to be linear to ±1 percent or better in all cases.

After one of the transducers had been placed in position in the fluid-container wall for evaluation, the device was assembled in the



a. MECHANICAL OPERATION



$R_{ab} = R_{cd} = R_{be} = R_{df} = R$; ALL $\Delta R \ll R$

$$\frac{\Delta R_{ab}}{R_{ab}} = (K_g)_{ab} \frac{\Delta L_{ab}}{L_{ab}} = K_g \frac{\Delta L}{L}$$

$$\frac{\Delta R_{cd}}{R_{cd}} = (K_g)_{cd} \frac{\Delta L_{cd}}{L_{cd}} = K_g \frac{\Delta L}{L}$$

$$\frac{\Delta R_{be}}{R_{be}} = (K_g)_{be} \frac{\Delta L_{be}}{L_{be}} = -K_g \frac{\Delta L}{L}$$

$$\frac{\Delta R_{df}}{R_{df}} = (K_g)_{df} \frac{\Delta L_{df}}{L_{df}} = -K_g \frac{\Delta L}{L}$$

$$\frac{e_{OUT}}{e_{IN}} = \frac{\Delta R_{ab} + \Delta R_{cd} - \Delta R_{be} - \Delta R_{df}}{4R}$$

$$\frac{e_{OUT}}{e_{IN}} = \frac{\Delta R}{R} = K_g \frac{\Delta L}{L}$$

b. ELECTRICAL OPERATION

Fig. 49. Schematic drawings depicting operation of flush-mounted pressure transducer.

auxiliary configuration as for an actual test. When the system had been balanced and the calibration steps recorded, the fluid chamber was pressurized in ten approximately equal steps, and the galvanometer excursion corresponding to each step in pressure was recorded. The procedure was then repeated in reverse, as the pressure was brought back to zero in ten approximately equal steps. The various pressure levels reached were determined from a bank (generally three) of Bourdon-type gages (Marsh Instrument Company, Type 210-3S, and Ashcroft Series 1082), each of which had been calibrated in a dead-weight tester (Ashcroft Portable Dead-Weight Tester, Type 13053-10) and placed in the load-application system (Fig. 50).

The results of a typical calibration test are shown in Fig. 51, where the maximum deviation from the best straight line through the points is approximately ±0.50 percent. Differences between data points obtained for the increasing steps and those obtained for the decreasing steps are not significant.

It should be noted that the mechanical-input values (or pressure equivalents) of all the calibration steps from A through F were determined. (Because Step G would have exceeded the linearity range of the galvanometer, its pressure equivalent was not determined.) If only the pressure equivalent of Step F had been determined, it would not be possible to use the transducer for any scale much greater than 4 in. = 1000 psi (e.g., 4 in. = 500 psi) without conducting a transducer calibration for that particular scale or one close to it; at a scale of 4 in. = 500 psi, Step F = 8 in., a value well beyond the linearity range of the galvanometer. (Recall that the concept of simulating a mechanical-input signal with the system-calibration circuit is valid only when the

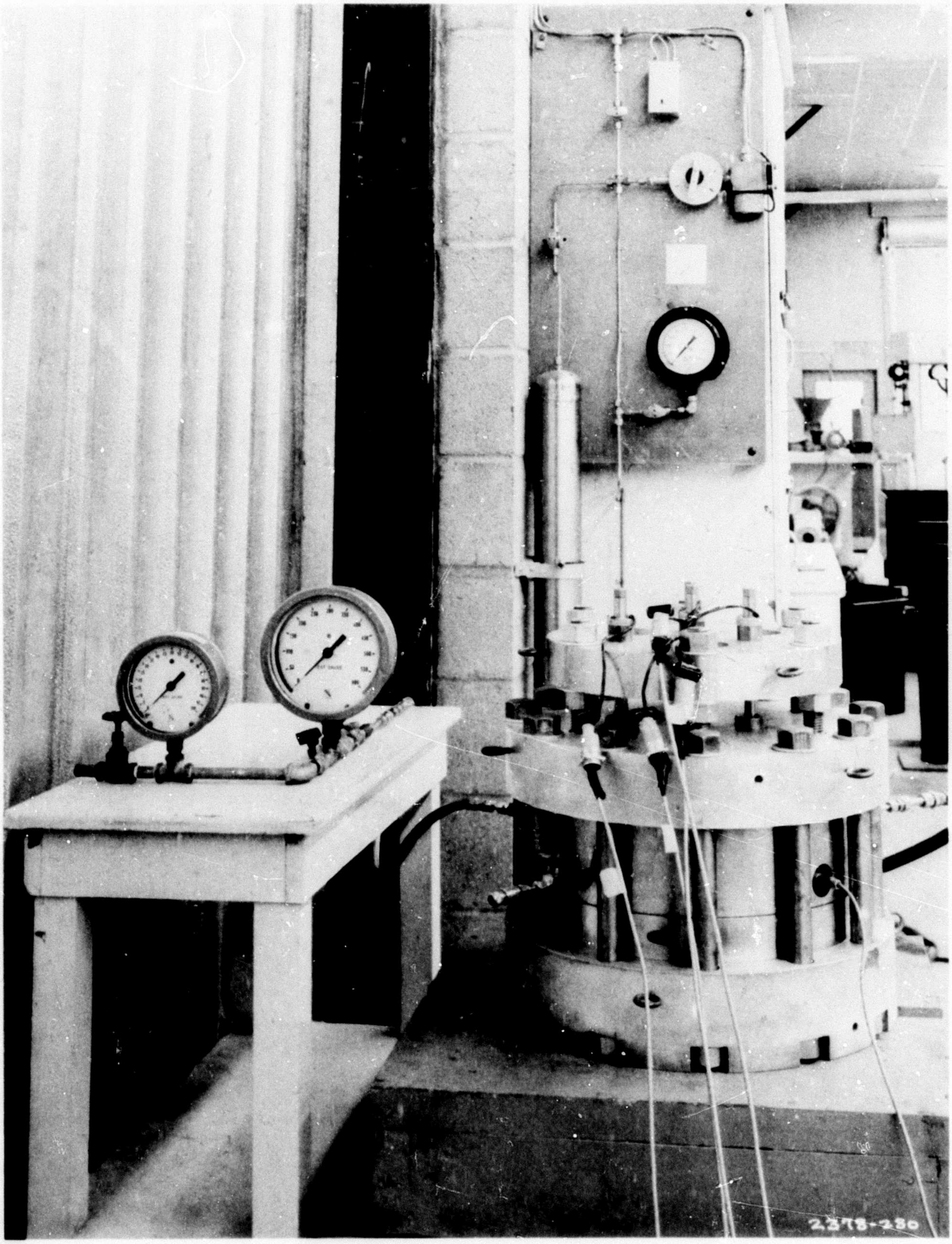


Fig. 50. Test setup for calibration of flush-mounted pressure transducer.

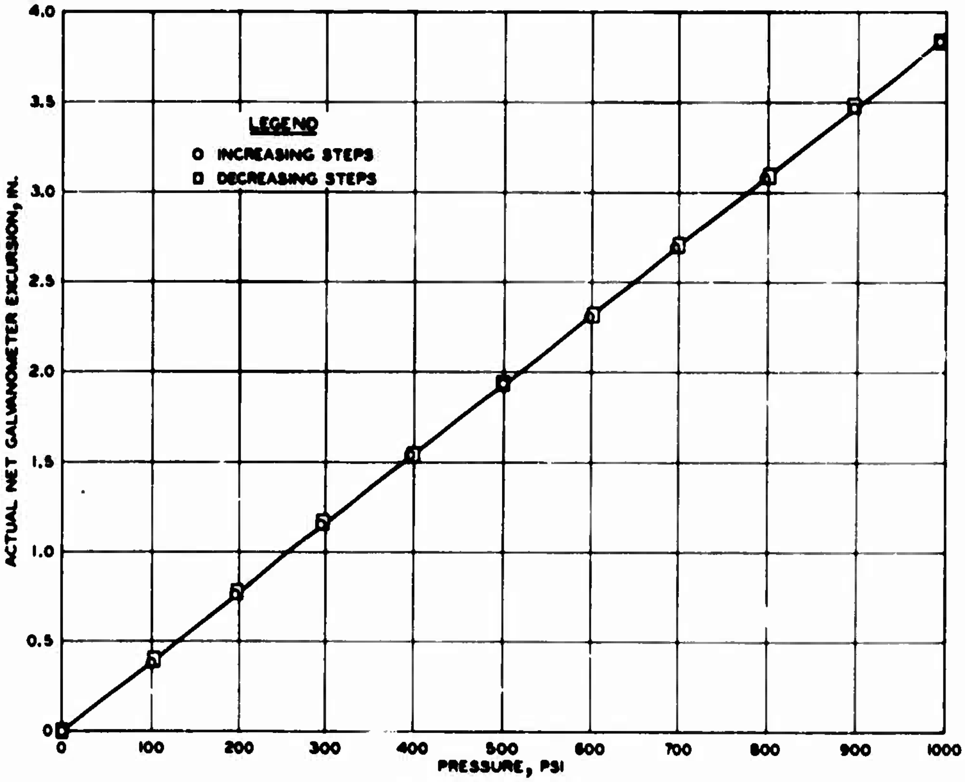
TRANSDUCER CALIBRATION
PRESSURE TRANSDUCER NO. 34133
CHANNEL 5

STATIC LINEARITY DETERMINATION

PRESSURE PSI	NET GALVANOMETER EXCURSION, IN. ACTUAL	NET GALVANOMETER EXCURSION, IN. NORMALIZED		NET GALVANOMETER EXCURSION, IN. ACTUAL	NET GALVANOMETER EXCURSION, IN. NORMALIZED		NET GALVANOMETER EXCURSION, IN. ACTUAL	NET GALVANOMETER EXCURSION, IN. NORMALIZED
0	0.00							
100	0.39							
197	0.76							
297	1.15							
397	1.54							
498	1.94							
598	2.31							
697	2.70							
797	3.08							
897	3.47							
996	3.84							
897	3.46							
801	3.08							
700	2.71							
601	2.32							
498	1.94							
398	1.54							
298	1.16							
199	0.77							
102	0.39							
0	0.00							
A	0.12							
B	0.25							
C	0.50							
D	1.00							
E	1.97							
F	3.87							

CALIBRATION TEST NUMBER	1		
BEST LINEAR RELATION FOR DATA	3.86" = 1000 PSI		
MAXIMUM DEVIATION FROM BEST LINEAR RELATION	0.02 INCH		
MECHANICAL-INPUT VALUES FOR CALIBRATION STEPS	E = 510 PSI, F = 1003 PSI		
NORMALIZED RELATION			

a. DATA TABULATION



b. DATA PLOT

Fig. 51. Results of typical calibration test for flush-mounted pressure transducer.

amplifier-recorder system is linear.) If, on the other hand, only the pressure equivalent of Step A had been determined, the accuracy of the transducer calibration would not be ± 1 percent, as specified, since the galvanometer excursion for Step A was only 0.12 in. Consequently, by determining the pressure equivalents of all the calibration steps (in the linear range), it was possible (1) to calibrate the transducer fairly accurately for all scales in the range 250 psi $\leq$ 4 in. $\leq$ 1000 psi, and (2) to obtain some indication of the calibration in the range 30 psi $\leq$ 4 in. $\leq$ 250 psi, for use as needed.

Repeatability. Some time after each of the pressure transducers had been calibrated and the pressure equivalents of the various calibration steps determined, the transducers were once again calibrated to provide a repeatability check for the pressure-equivalent values originally obtained. Repeatability checks were conducted with the equipment assembled in both test configurations. The pressure-equivalent values, for which the galvanometer excursions were at least 2 in., were found to be repeatable to better than 1 percent. (Pressure-equivalent values, for which the galvanometer excursion varied from 2 in. to 0.1 in., were found to be repeatable from 1 to 10 percent, roughly corresponding to the resolution capability for the corresponding galvanometer excursions.)

The results of a typical repeatability check are shown in Fig. 52, in which the repeatability (Test No. 2 relative to Test No. 1) is shown to be approximately 0.5 percent (as reflected by the pressure-equivalent values determined for Steps E and F).

Approximately one month after the second of the two calibration tests mentioned above had been conducted, the transducer failed during an

equipment-compressibility test (cause unknown), and it was returned to the manufacturer for repairs. When the transducer had been repaired and returned to WES, a third calibration was conducted to determine if the previous calibrations were valid. The results of the third calibration test are included in Fig. 53. Clearly, even though the transducer had been damaged and repaired, and even though a different pressure fluid was used, the calibration remained unchanged.

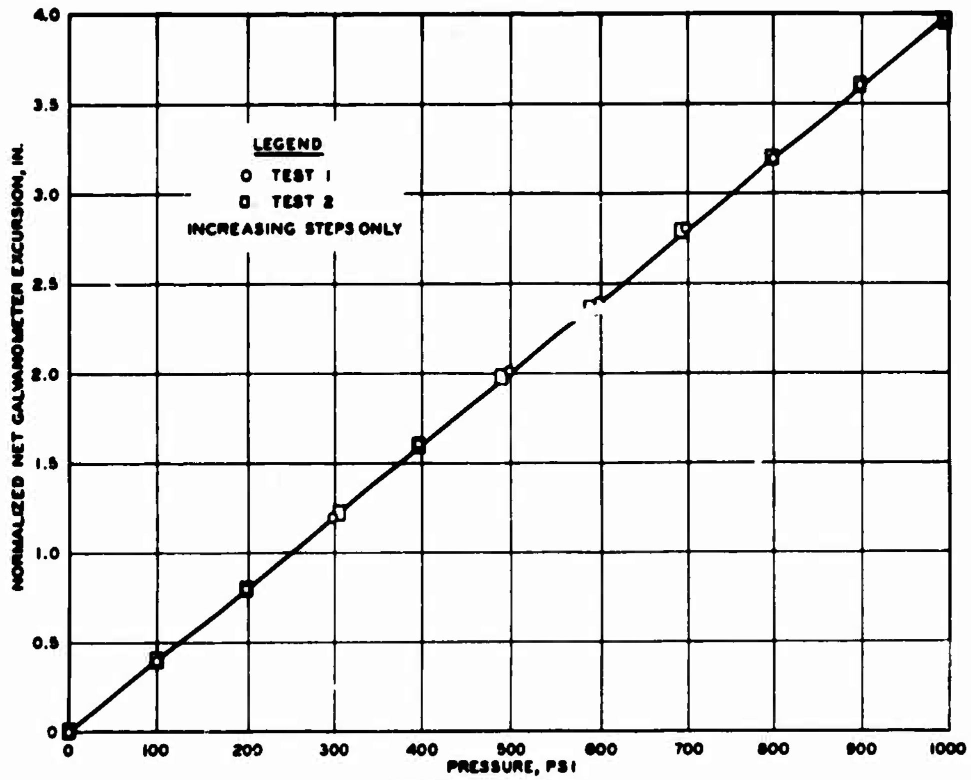
The pressure-equivalent values obtained from calibration tests conducted under the Dynapak loader were found to be the same as those obtained from calibration tests conducted in the test area used for long-duration tests. Because different sets of cables were used for tests in the two test areas, there was a possibility that the results would be different. The results of a pair of calibration tests conducted for the same transducer unit in the two test areas are shown in Fig. 54.

Drift. Information concerning drift in the output signal from the flush-mounted pressure transducer was obtained by recording the galvanometer excursion as a function of time for a constant value of pressure. Each of the transducer units used was evaluated at zero pressure and at or near peak rated pressure. The data were recorded over a period of 2 hr, at 15-min intervals. In all cases, the drift from the initial position was found to be less than or equal to 0.02 in.

Frequency Response. An indication of the frequency-response characteristics of the flush-mounted pressure transducer was obtained by comparing the pressure-time relationship provided by it with the pressure-time relationship provided by the piezoelectric pressure transducer. No significant differences were found, and it was concluded that the

TRANSDUCER CALIBRATION PRESSURE TRANSDUCER NO 34139 CHANNEL 8 REPEATABILITY CHECK	PRESSURE PSI	NET GALVANOMETER EXCURSION, IN.		PRESSURE PSI	NET GALVANOMETER EXCURSION, IN.	
		ACTUAL	NORMALIZED		ACTUAL	NORMALIZED
	0	0.00	0.00	0	0.00	0.00
	100	0.39	0.39	100	0.40	0.40
	197	0.76	0.79	198	0.80	0.79
	297	1.16	1.19	294	1.23	1.22
	397	1.54	1.60	396	1.60	1.59
	499	1.94	2.01	499	1.98	1.97
	598	2.31	2.39	598	2.38	2.38
	697	2.70	2.80	692	2.80	2.79
	797	3.08	3.19	796	3.21	3.18
	897	3.47	3.60	898	3.62	3.60
	994	3.84	3.99	999	3.99	3.96
	897	3.48	3.61	896	3.64	3.62
	801	3.09	3.20	800	3.23	3.21
	700	2.71	2.81	700	2.84	2.82
	601	2.32	2.40	606	2.46	2.45
	499	1.94	2.01	503	2.05	2.04
	399	1.54	1.60	404	1.65	1.64
	298	1.16	1.20	302	1.23	1.22
	199	0.77	0.80	200	0.85	0.84
	102	0.39	0.40	101	0.42	0.42
	0	0.00	0.00	0	0.01	0.00
	A	0.12	0.13	A	0.13	0.13
	B	0.25	0.26	B	0.26	0.26
	C	0.88	0.91	C	0.92	0.92
	D	1.00	1.03	D	1.04	1.03
	E	1.97	2.04	E	2.06	2.04
	F	3.87	4.00	F	[illegible].92	3.90
CALIBRATION TEST NUMBER	1			2		
BEST LINEAR RELATION FOR DATA	3.86" = 1000 PSI			4.03" = 1000 PSI		
MAXIMUM DEVIATION FROM BEST LINEAR RELATION	0.02 INCH			0.02 INCH		
MECHANICAL-INPUT VALUES FOR CALIBRATION STEPS	E = 510 PSI, F = 1003 PSI			E = 508 PSI, F = 989 PSI		
NORMALIZED RELATION	4.00" = 1000 PSI			4.00" = 1000 PSI		

a. DATA TABULATION



b. DATA PLOT

Fig. 52. Results of typical repeatability check on calibration of flush-mounted pressure transducer.

TRANSDUCER CALIBRATION
PRESSURE TRANSDUCER NO. 34133
CHANNEL 5

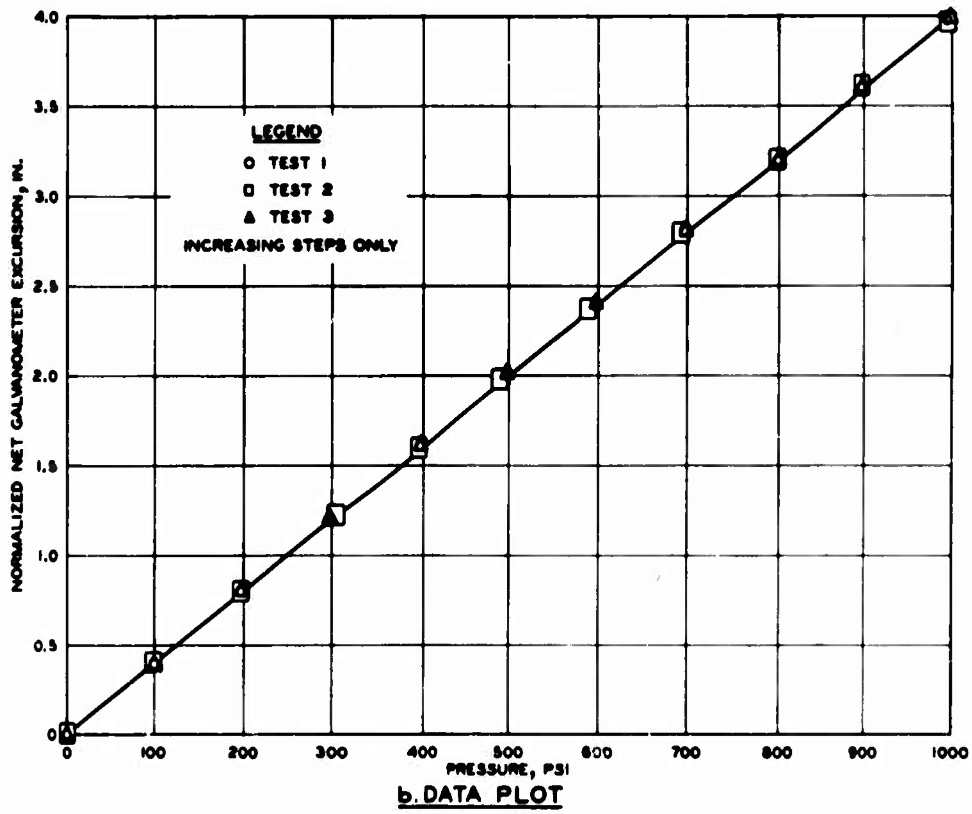
REPEATABILITY CHECK

NOTE: TEST 3 DIFFERED FROM TESTS 1 AND 2 IN TWO WAYS: (1) THE PRESSURE FLUID USED FOR TEST 3 WAS WATER WHEREAS NITROGEN WAS USED FOR TESTS 1 AND 2, AND (2) TEST 3 WAS CONDUCTED AFTER THE TRANSDUCER HAD FAILED, BEEN RETURNED TO AND REPAIRED BY THE MANUFACTURER, AND BEEN RETURNED TO WES

PRESSURE PSI	NET GALVANOMETER EXCURSION, IN.		PRESSURE PSI	NET GALVANOMETER EXCURSION, IN.		PRESSURE PSI	NET GALVANOMETER EXCURSION, IN.	
	ACTUAL	NORMALIZED		ACTUAL	NORMALIZED		ACTUAL	NORMALIZED
0	0.00	0.00	0	0.00	0.00	1	0.00	0.00
100	[illegible]	[illegible]	100	0.40	0.40	100	[illegible]	[illegible]
197	0.76	0.79	198	0.80	0.79	199	0.79	0.80
297	1.15	1.19	304	1.23	1.22	299	1.19	1.20
397	1.64	1.60	396	1.60	1.60	399	1.59	1.61
[illegible]	1.96	2.01	490	1.98	1.97	400	1.99	2.01
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.40
607	2.70	2.80	603	2.80	2.79	600	2.77	2.80
707	3.08	3.19	706	3.21	3.19	800	3.17	3.20
807	3.47	3.60	[illegible]	3.62	3.60	[illegible]	3.57	3.61
[illegible]	3.84	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
807	3.48	3.61	[illegible]	3.64	3.62	801	3.57	3.61
801	[illegible]	[illegible]	800	3.23	3.21	801	3.10	3.21
700	2.71	2.81	[illegible]	2.84	2.83	701	2.79	2.82
601	2.32	2.40	[illegible]	[illegible]	2.43	[illegible]	[illegible]	2.40
400	1.94	2.01	501	2.06	2.04	500	1.98	2.00
[illegible]	1.54	[illegible]	404	1.66	1.64	[illegible]	1.59	1.61
[illegible]	1.16	1.20	302	1.23	1.22	[illegible]	1.19	1.20
199	0.77	[illegible]	200	[illegible]	0.84	[illegible]	0.80	0.81
102	[illegible]	0.40	101	0.42	0.42	100	0.40	0.40
0	0.00	0.00	0	0.01	0.00	0	0.00	0.00
A	0.12	0.13	A	0.13	0.13	A	0.13	0.13
B	[illegible]	[illegible]	B	0.26	0.26	B	[illegible]	0.26
C	[illegible]	0.51	C	0.52	0.52	C	0.52	0.53
D	1.00	1.05	D	1.04	1.05	D	1.03	1.04
E	1.97	2.04	E	2.06	2.04	E	2.02	2.04
F	3.87	4.00	F	4.02	3.99	F	3.97	4.01

CALIBRATION TEST NUMBER	1	2	3
BEST LINEAR RELATION FOR DATA	[illegible]" = 1000 PSI	4.02" = 1000 PSI	[illegible]" = 1000 PSI
MAXIMUM DEVIATION FROM BEST LINEAR RELATION	0.02 INCH	0.02 INCH	0.01 INCH
MECHANICAL-INPUT VALUES FOR CALIBRATION STEPS	E = 510 PSI, F = 1003 PSI	E = [illegible] PSI, F = [illegible] PSI	E = 510 PSI, F = 1003 PSI
NORMALIZED RELATION	4.00" = 1000 PSI	4.00" = 1000 PSI	4.00" = 1000 PSI

a. DATA TABULATION



b. DATA PLOT

Fig. 53. Results of calibration tests for flush-mounted pressure transducer showing repeatability in spite of transducer repair and change in pressure fluid.

TRANSDUCER CALIBRATION
PRESSURE TRANSDUCER NO [illegible]
CHANNEL 5

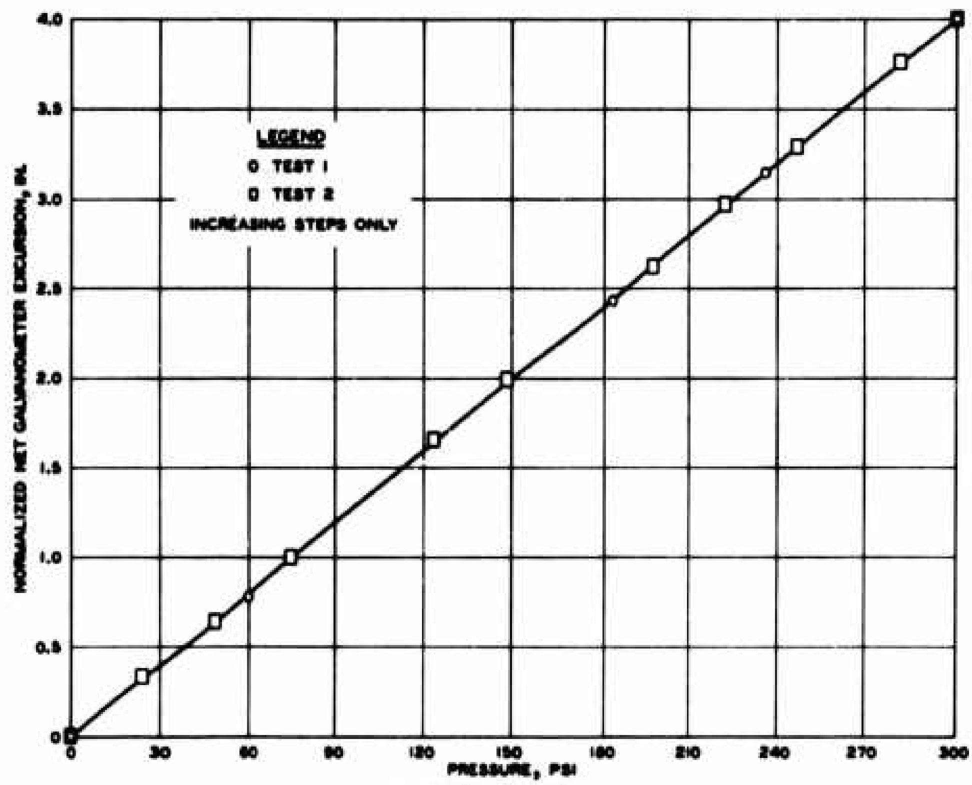
REPEATABILITY CHECK

NOTE: TEST 1 WAS CONDUCTED UNDER THE DYNAPAK LOADER, AND TEST 2 WAS CONDUCTED IN THE TEST AREA USED FOR LONG-DURATION TESTS

PRESSURE, PSI	NET GALVANOMETER EXCURSION, IN. ACTUAL	NET GALVANOMETER EXCURSION, IN. NORMALIZED	PRESSURE, PSI	NET GALVANOMETER EXCURSION, IN. ACTUAL	NET GALVANOMETER EXCURSION, IN. NORMALIZED		NET GALVANOMETER EXCURSION, IN. ACTUAL	NET GALVANOMETER EXCURSION, IN. NORMALIZED
0	0.00	0.00	0	0.00	0.00			
60	0.77	0.79	24.5	0.32	0.33			
183	2.38	2.44	48	0.62	0.64			
236	3.08	3.16	75	0.96	1.00			
300	3.93	4.01	124	1.60	1.66			
236	3.07	3.15	140	1.82	1.90			
179	2.36	2.40	188	2.53	2.64			
117	1.53	1.56	222.5	2.87	2.97			
58	0.76	0.77	247	3.18	3.30			
0	0.00	0.00	282	3.64	3.77			
			300	3.87	4.01			
			278	3.53	3.66			
			240	3.20	3.32			
			225	2.89	3.00			
			201	2.58	2.68			
			151	1.92	1.99			
			126	1.60	1.66			
			76	0.96	1.00			
			48	0.62	0.64			
			23	0.30	0.31			
			0	0.00	0.00			
A	0.11	0.11	A	0.11	0.11			
B	0.23	0.24	B	0.22	0.23			
C	0.46	0.47	C	0.46	0.47			
D	0.92	0.94	D	0.90	0.93			
E	1.83	1.88	E	1.77	1.83			
F	3.56	3.66	F	3.50	3.62			

CALIBRATION TEST NUMBER	1	2	
BEST LINEAR RELATION FOR DATA	3.92" = 300 PSI	3.86" = 300 PSI	
MAXIMUM DEVIATION FROM BEST LINEAR RELATION	0.01 INCH	0.02 INCH	
MECHANICAL-INPUT VALUES FOR CALIBRATION STEPS	F = 274 PSI	F = 272 PSI	
NORMALIZED RELATION	4.00" = 300 PSI	4.00" = 300 PSI	

a. DATA TABULATION



b. DATA PLOT

Fig. 54. Results of calibration tests for flush-mounted pressure transducer showing repeatability in spite of change in test area.

frequency-response characteristics of the flush-mounted transducer were quite satisfactory.

The pressure-time relationships provided by the two transducers for the two fastest loading pulses in the test program are shown in Fig. 55. (The various curves and lines shown were traced directly from the oscillograph records.) Effective rise times for the two tests are approximately 4 msec for Test No. A01P01 and 6 msec for Test No. A01P02. In each test, the two pressure-time curves are clearly almost identical. The amplitude ratio (flush-mounted-transducer signal relative to piezoelectric-transducer signal, at a given instant of time) varies from 1.00 to 0.98, and the time lag from 0 to 0.2 msec. (It should be noted that the amplitude ratio differs from unity by as much as 2 percent only for Test No. A01P01, for which the effective rise time was faster than the fastest permissible for 1 percent accuracy, according to Equation 2.1.)

Since the same transducer unit was used for all the short-duration tests in the preliminary testing program, there is no information available concerning the frequency-response characteristics of any of the other units. All of the units are of the same type, however, and in the absence of any information to the contrary it may be assumed that the frequency-response characteristics of all the units are satisfactory.

Resolution. Resolution of the flush-mounted pressure transducer, as specified by the manufacturer, is infinite, indicating that there are no limitations in the transducer itself. With the 0- to 100-psi unit obtained, it is theoretically possible to resolve less than 0.01 psi at the maximum gain setting on Attenuator 1; with the 0- to 1000-psi unit, pressures as large as 1000 psi can be measured. Clearly, any pressure of

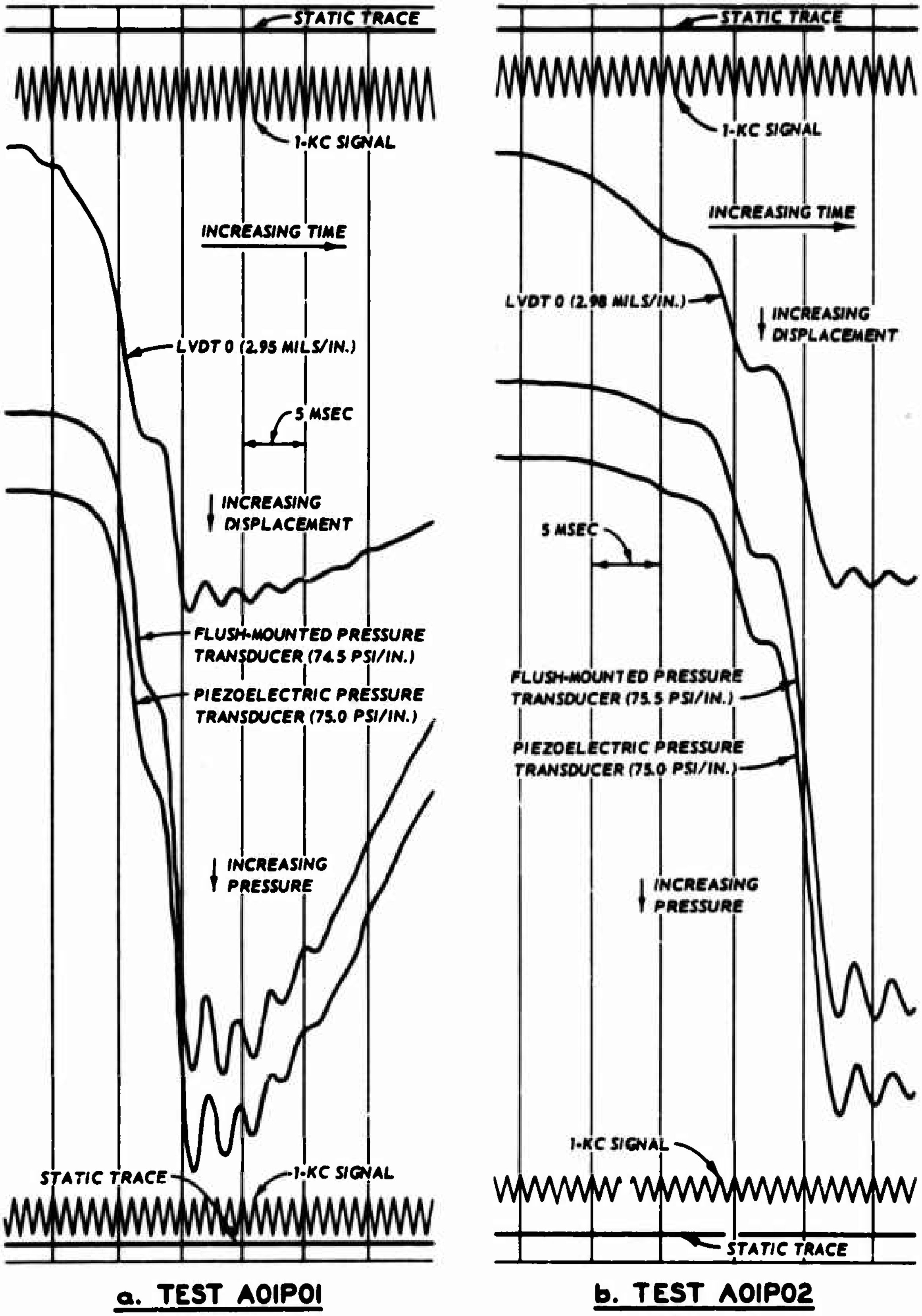


Fig. 55. Oscillograph records for two fastest pressure pulses in test program.

interest can be recorded with the units available, with the existing amplifier-recorder system.

4.5.3 Key Measurement for Strain

A photograph of one of the LVDT displacement transducers used to determine the vertical strain in the specimen as a function of time is shown in Fig. 28. Schematic drawings depicting the mechanical and electrical operation of the transducer are shown in Fig. 56.

When the core is in a central (or null) position, the voltages induced in the two outer or secondary coils are the same. Since the two secondary coils are connected in phase, as shown, the two induced voltages cancel, and a zero output voltage results. As the core moves downward, the voltage induced in the lower secondary coils becomes larger than that induced in the upper secondary coils, and a positive output voltage is generated by the transducer. Similarly, an upward core movement causes a negative output voltage to be generated. The LVDT is designed to cause a net output voltage that is directly proportional to the core motion.

The LVDT transducer itself could not be used in conjunction with the calibration-control circuit (since the LVDT is an inductive transducer and does not contain a resistive-bridge circuit), and a dummy resistive bridge was prepared which replaced the LVDT during system calibration (Fig. 43). It is important to note that although the transduction circuit for the LVDT is inductive rather than resistive, it is nonetheless linear (theoretically, and as verified by the manufacturer's calibration). It follows, therefore, that the galvanometer excursion provided by one of the calibration steps (in the linear range) is proportional to--and not simply indicative of--the degree of amplification, and the calibration steps can

be considered to represent or simulate a certain core motion. Consequently, although the system-calibration procedure is somewhat more complex for the LVDT transducer than it is for the simple strain-gage transducer, the inherent versatility of the calibration-control circuit for linear systems (as discussed above) is available to both types of transducers.

The particular model LVDT selected, both for the key displacement measurement and for the three other displacement measurements, was a Schaevitz Engineering Type XS-LB (Section 3.6). Four units were obtained in both the ±60-mil range and the ±300-mil range, so that the full range of anticipated displacements would be resolvable (see discussion below). Since only the lower-range units were found to be required for the preliminary testing program, however, the higher-range units were not evaluated.

When the four LVDT units in each range were obtained, each unit was marked for a particular position in the device. Only the ±60-mil unit for LVDT No. 0, the transducer for the key displacement measurement, was subjected to an intensive evaluation, the results of which are reviewed below. The other ±60-mil units were calibrated, as required, and repeatability checks were conducted under a few conditions (selected at random). Since all four units were of the same type, it was assumed that the characteristics of all were the same.

Static Linearity. In the overall circuit used by the manufacturer of the LVDT to verify its linearity, the input frequency was 60 cps and the load on the LVDT (i.e., impedance to the output voltage) was 500,000 ohms. In the measurement system selected for the one-dimensional compression device at WES, the input frequency is 3000 cps (3 kc) and the load on the LVDT (i.e. the amplifier-recorder system) is 1200 ohms. Since

the static-linearity characteristics of an LVDT transducer are known to vary with both input frequency and load, it was not surprising to find that the first few calibrations were highly nonlinear. The basic LVDT circuit shown in Fig. 56 was modified in several ways (by trial and error), until a circuit was found which provided the required degree of linearity (Fig. 57).

It was found that, with the circuit shown (and with the given amplifier-recorder circuit, Fig. 44), a full-scale, 4-in. galvanometer excursion could be obtained for core displacements varying from 1.5 to 80 mils. For an attenuator setting of 1 (i.e., on Attenuator 1), the gain setting could be varied to provide any galvanometer excursion-core displacement relationship from 4 in. = 1.5 mils to 4 in. = 5 mils; on Attenuator 4, the relationship could be varied from 4 in. = 5 mils to 4 in. = 20 mils; and, on Attenuator 16, the relationship could be varied from 4 in. = 20 mils to 4 in. = 80 mils. It was convenient, therefore, to limit the use of the LVDT to these three attenuators, and to refer to any scale on Attenuator 1 as fine, any scale on Attenuator 4 as medium, and any scale on Attenuator 16 as coarse.

The first few exploratory calibrations, during which the LVDT circuit modifications were evaluated, were conducted in a standard micrometer stand removed from the device. However, because there was some concern about the effect of the various metal components in the vicinity of the LVDT (see Fig. 14) on the behavior of the inductive transducer, all the actual transducer calibrations were conducted with the LVDT in place in the same physical environment as it is found during an actual test. For a typical calibration test, the equipment was assembled as for an actual test except that neither a specimen nor a flexible membrane was used. At first,

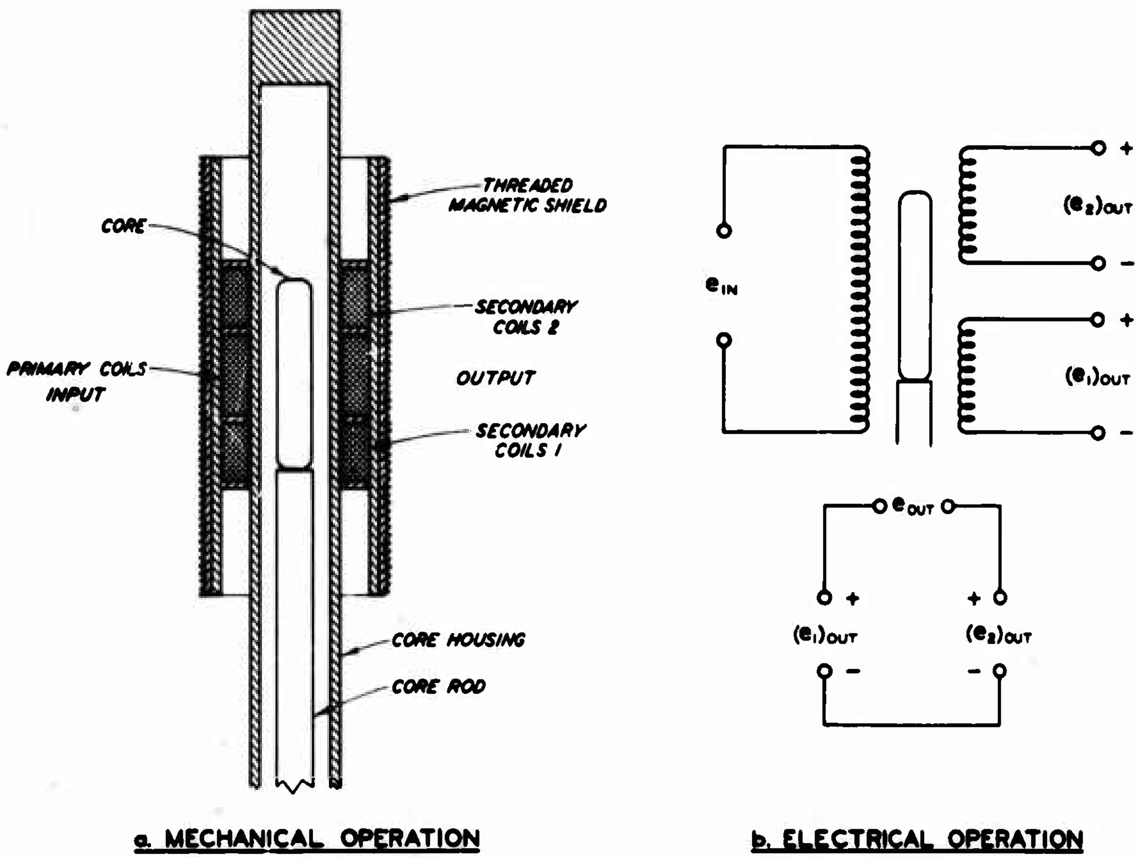


Fig. 56. Schematic drawings depicting operation of LVDT displacement transducer.

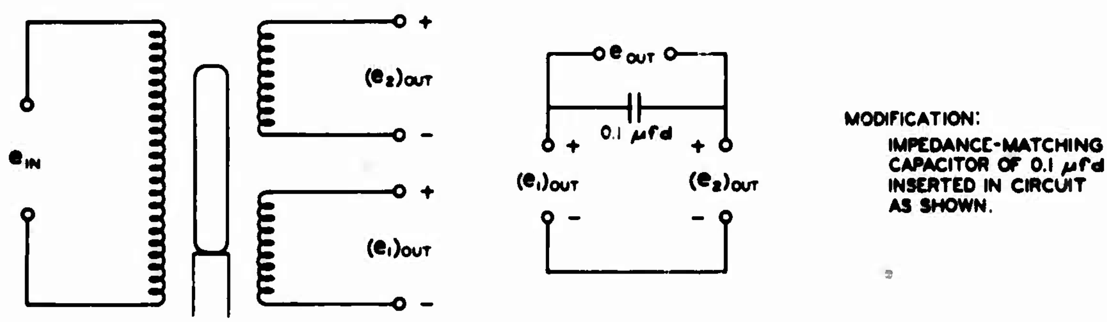
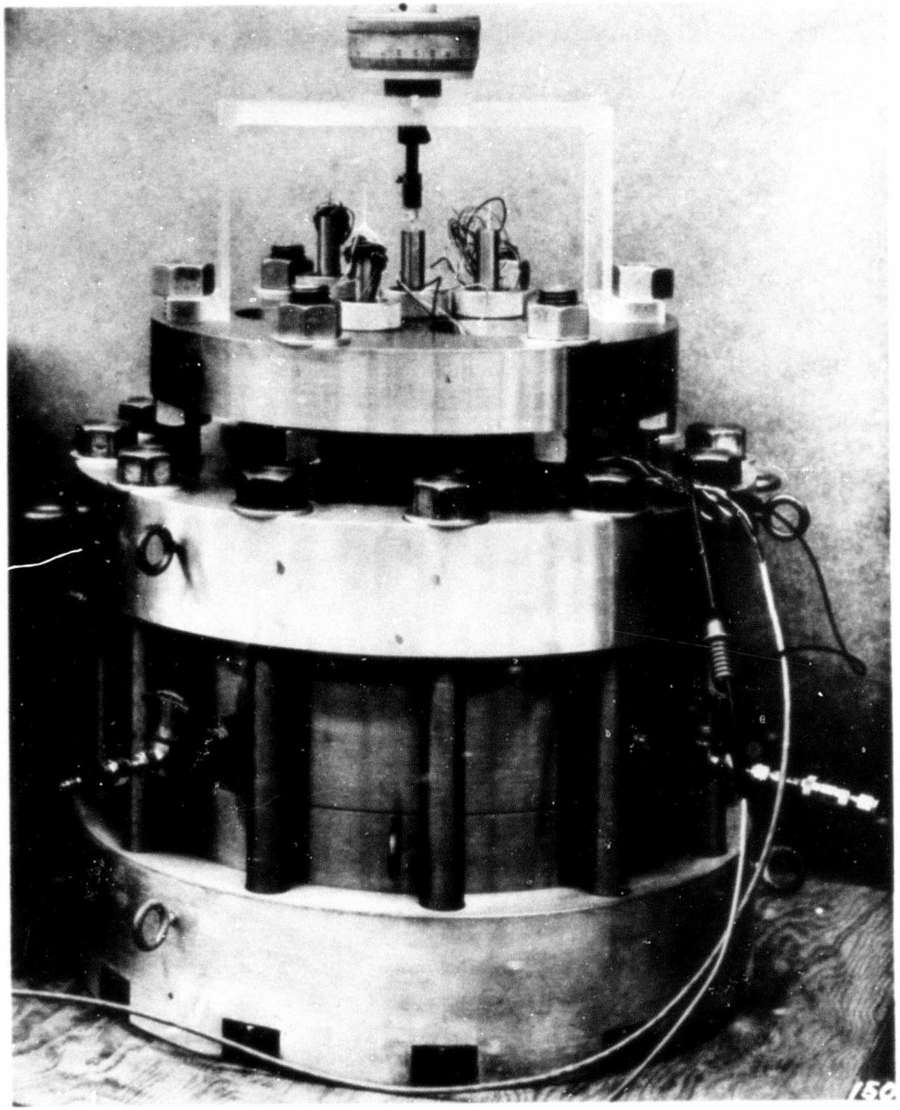
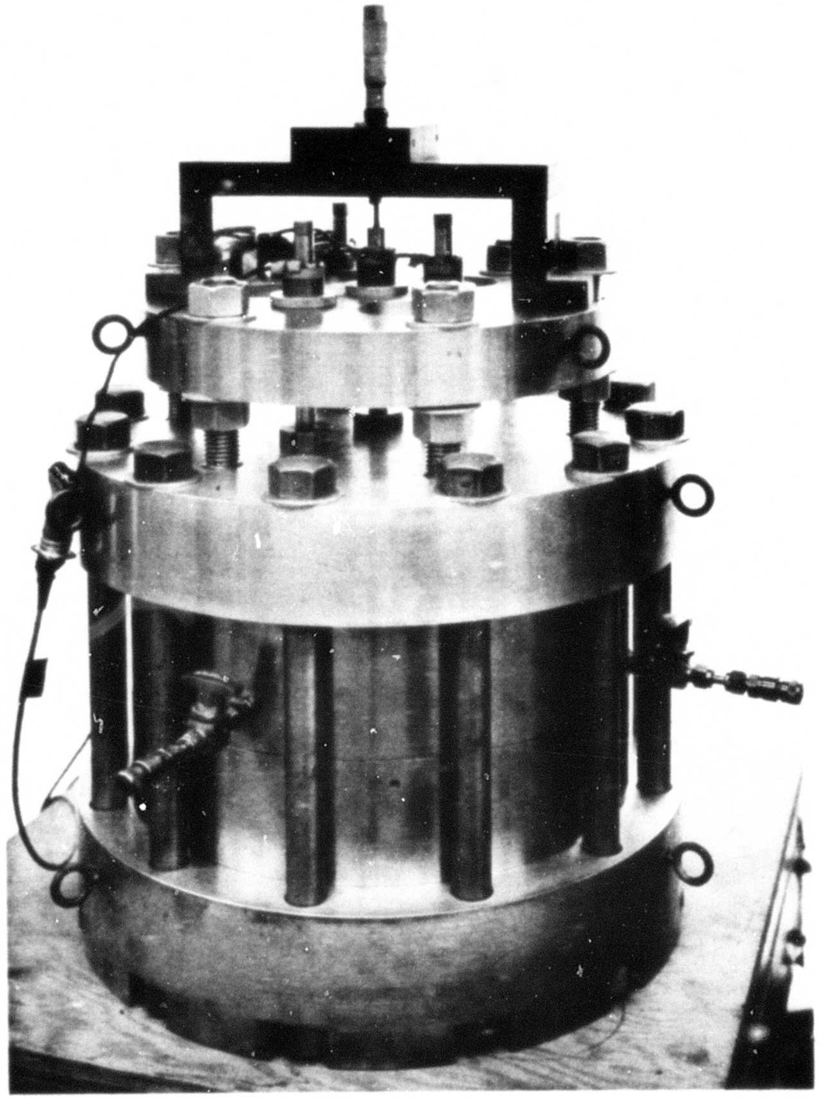


Fig. 57. Schematic drawing of modified circuit for LVDT displacement transducer.

the micrometer was supported on a Plexiglas frame (which was rigidly connected to the coil support plate) and coupled to the LVDT core by a thin wooden rod which passed through the bleed hole of the core housing (Fig. 58a). When this configuration proved to be too flexible for the precision required, the Plexiglas frame was replaced by a thicker phenolic frame, and the wooden rod was replaced by a phenolic rod (Fig. 58b). (The micrometer shown in Fig. 58b was used for only a few calibration tests, after which use of the micrometer shown in Fig. 58a was resumed.) After the micrometer had been connected to the core, the position of the coils was adjusted until the LVDT was nulled. The measurement system was then balanced, the calibration steps recorded, and the coils adjusted to the desired starting position (generally several mils above the null position, to avoid passing through the relatively insensitive null region during the calibration). After the coils had been rigidly clamped to the coil support plate by a knurled, brass clamping collar (Fig. 58), the position of the galvanometer was mechanically reset to compensate for the difference between the null position for the LVDT and the starting position for the calibration. The core was then lowered in ten approximately equal steps, and the galvanometer excursion corresponding to each step was recorded. The procedure was repeated in reverse, as the core was raised back to the starting position in ten approximately equal steps. The various core positions were determined from the micrometer readings. (The smallest micrometer division was 0.1 mil.) It should be noted that the calibrations were not conducted under pressure; however, since the only part of the displacement transducer included in the pressure environment is the inert core, it may be assumed



a. ORIGINAL SETUP WITH PLEXIGLAS FRAME AND WOODEN ROD



b. MODIFIED SETUP WITH PHENOLIC FRAME AND ROD

Fig. 58. Test setup for calibration of LVDT displacement transducer.

with a fair degree of confidence that pressure has no effect on the behavior of the transducer.

The relationship between core movement and galvanometer excursion was determined statically for each of the three attenuator settings (i.e., in the coarse, medium, and fine ranges of the LVDT), and it was found to be linear to ± 1 percent or better in each case.

The results of a typical calibration test (conducted on Attenuator 4, with maximum gain) are shown in Fig. 59, where it can be seen that the maximum deviation from the best straight line through the points is approximately ± 0.25 percent. Differences between data points obtained for the increasing steps and those obtained for the decreasing steps are not significant.

Since it was recognized that any permissible scale might be required at some time in the test program (unlike the peak pressure, which is the independent variable for nearly all tests, the peak surface displacement cannot be programmed in advance to take on an even value), it was decided to conduct calibration tests at both minimum and maximum gain settings for each attenuator setting. It was felt that, in this way, accurate displacement-equivalent values would be obtained for all calibration steps. On Attenuator 1, where this technique could not be used (at maximum gain, Calibration Step A causes a galvanometer excursion of approximately 5.4 in., which is beyond the linearity range of the galvanometer), a calibration test was conducted at a medium gain setting. In summary, calibration tests were conducted at scales of 4 in. = 80 mils and 4 in. = 20 mils on Attenuator 16, at scales of 4 in. = 20 mils and 4 in. = 5 mils on Attenuator 4, and at a scale of 4 in. = 3 mils on Attenuator 1.

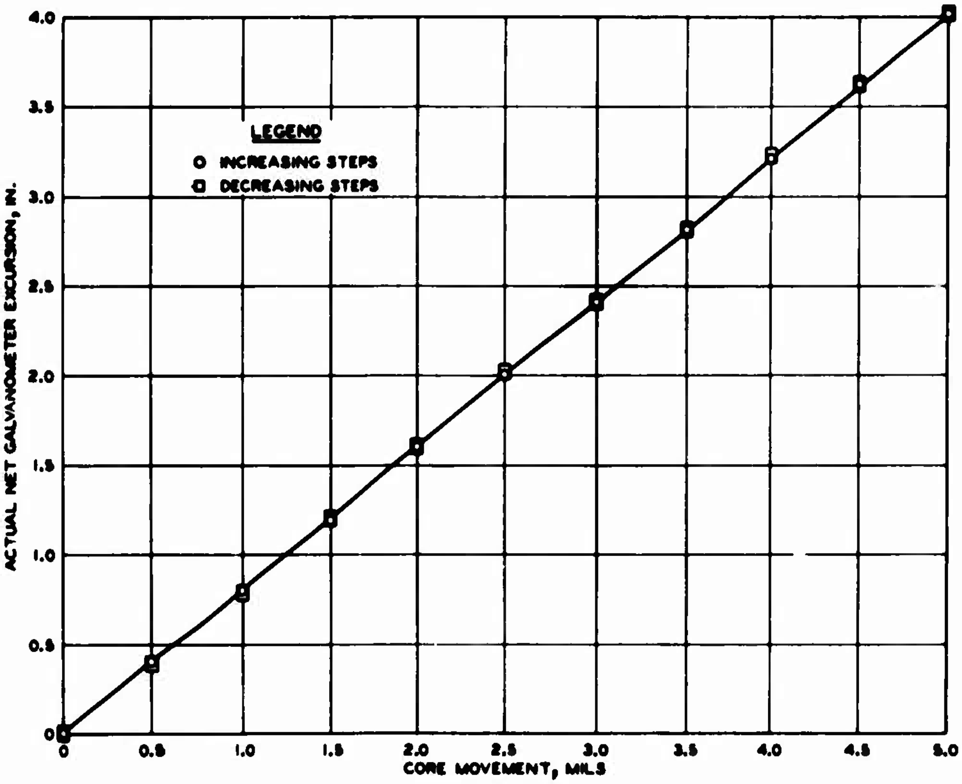
TRANSDUCER CALIBRATION
LVDT NO. 0; MEDIUM RANGE
CHANNEL 1

STATIC LINEARITY DETERMINATION

CORE MOVEMENT MILS	NET GALVANOMETER EXCURSION, IN			NET GALVANOMETER EXCURSION, IN			NET GALVANOMETER EXCURSION, IN	
	ACTUAL	NORMALIZED		ACTUAL	NORMALIZED		ACTUAL	NORMALIZED
0.0	0.00							
0.5	0.40							
1.0	0.80							
1.5	1.19							
2.0	1.60							
2.5	2.00							
3.0	2.41							
3.5	2.81							
4.0	3.21							
4.5	3.62							
5.0	4.01							
4.5	3.62							
4.0	3.22							
3.5	2.81							
3.0	2.41							
2.5	2.01							
2.0	1.60							
1.5	1.20							
1.0	0.79							
0.5	0.39							
0.0	-0.01							
A	1.87							
B	3.10							

CALIBRATION TEST NUMBER	1		
BEST LINEAR RELATION FOR DATA	4.01" = 5 MILS		
MAXIMUM DEVIATION FROM BEST LINEAR RELATION	0.01 INCH		
MECHANICAL-INPUT VALUES FOR CALIBRATION STEPS	B = 3.87 MILS		
NORMALIZED RELATION			

a. DATA TABULATION



b. DATA PLOT

Fig. 59. Results of typical calibration test for LVDT displacement transducer.

It should be noted that the starting position for the LVDT coils in the various calibration tests conducted in the 0- to 80-mil range was 40 mils below its null position (i.e., the core was 40 mils above its null position relative to the coils). Since the LVDT's used were ±60-mil units, it was not possible to obtain an 80-mil calibration without the core passing through the null position during the calibration. Although the null region is relatively insensitive--and, consequently, nonlinear relative to other regions--it is also very small and, therefore, insignificant (in that it cannot be resolved) in the coarse 0- to 80-mil range.

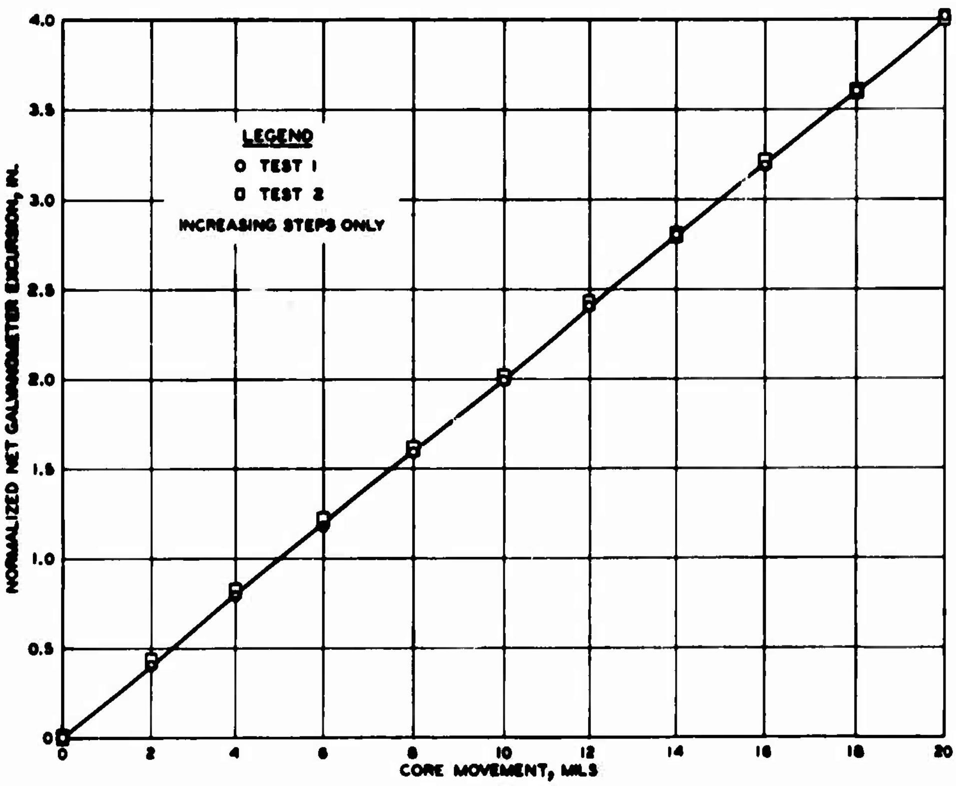
Repeatability. Some time after the LVDT transducer had been calibrated and the displacement equivalents of the various calibration steps determined, the transducer was once again calibrated to provide a repeatability check for the displacement-equivalent values originally obtained. Repeatability checks were conducted in the test area used for long-duration tests, with the equipment assembled in the auxiliary configuration, at each of the five scales for which calibration tests were originally conducted. Additional repeatability checks were conducted under the Dynapak, with the equipment assembled in the principal configuration. In all cases, the displacement-equivalent values, for which the galvanometer excursions were at least 2 in., were found to be repeatable to better than 2 percent (±1 percent from a mean value).

The results of a typical repeatability check are shown in Fig. 60 where it is shown that the repeatability (Test No. 2 relative to Test No. 1) was found to be approximately 1.25 percent (as reflected by the displacement-equivalent values determined for Step D).

The displacement-equivalent values obtained from calibration

TRANSDUCER CALIBRATION LVDT NO. 0; COARSE RANGE CHANNEL 1 REPEATABILITY CHECK	CORE MOVEMENT MILS	NET GALVANOMETER EXCURSION, IN. ACTUAL	NET GALVANOMETER EXCURSION, IN. NORMALIZED	CORE MOVEMENT MILS	NET GALVANOMETER EXCURSION, IN. ACTUAL	NET GALVANOMETER EXCURSION, IN. NORMALIZED		NET GALVANOMETER EXCURSION, IN. ACTUAL	NET GALVANOMETER EXCURSION, IN. NORMALIZED
	0	0.00	0.00	0	0.00	0.00			
	2	0.40	0.40	2	0.42	0.42			
	4	0.79	0.79	4	0.82	0.81			
	6	1.19	1.18	6	1.22	1.21			
	8	1.60	1.59	8	1.62	1.60			
	10	2.00	1.99	10	2.02	2.00			
	12	2.41	2.40	12	2.43	2.41			
	14	2.81	2.80	14	2.83	2.80			
	16	3.21	3.19	16	3.24	3.21			
	18	3.62	3.60	18	3.64	3.60			
	20	4.04	4.02	20	4.04	4.00			
	18	3.62	3.60	18	3.64	3.60			
	16	3.22	3.20	16	3.23	3.20			
	14	2.81	2.80	14	2.82	2.79			
	12	2.41	2.40	12	2.43	2.40			
	10	2.00	1.99	10	2.02	2.00			
	8	1.60	1.59	8	1.62	1.60			
	6	1.19	1.17	6	1.22	1.21			
	4	0.79	0.79	4	0.81	0.80			
	2	0.39	0.39	2	0.42	0.42			
	0	-0.01	-0.01	0	-0.02	-0.02			
	A	0.40	0.40	A	0.40	0.40			
	B	0.80	0.80	B	0.79	0.79			
	C	1.60	1.59	C	1.58	1.56			
	D	3.16	3.14	D	3.14	3.11			
CALIBRATION TEST NUMBER				2					
BEST LINEAR RELATION FOR DATA	4.02" = 20 MILS			4.04" = 20 MILS					
MAXIMUM DEVIATION FROM BEST LINEAR RELATION	0.03 INCH			0.02 INCH					
MECHANICAL-INPUT VALUES FOR CALIBRATION STEPS	D = 15.7 MILS			D = 15.6 MILS					
NORMALIZED RELATION	4.00" = 20 MILS			4.00" = 20 MILS					

a. DATA TABULATION



b. DATA PLOT

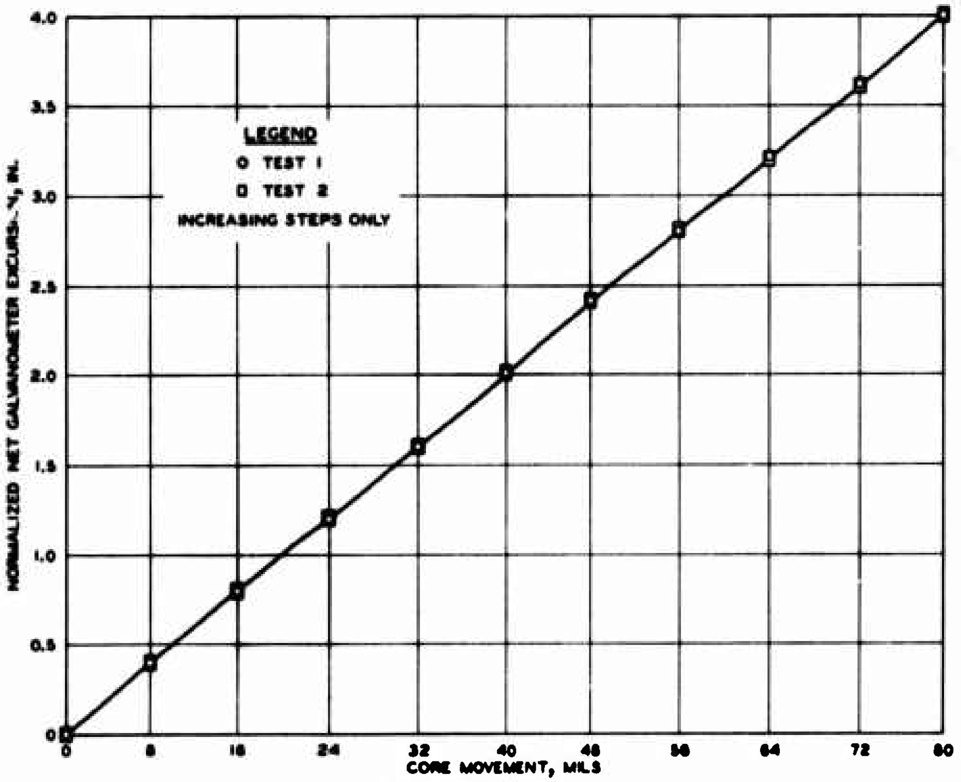
Fig. 60. Results of typical repeatability check on calibration of LVDT displacement transducer.

tests conducted under the Dynapak loader were found to be the same as those obtained from calibration tests conducted in the test area used for long-duration tests. Because different sets of cables were used for tests in the two test areas, and because the magnetic environment was very much different in the two areas, there was a possibility that the results would be different. The results of a pair of calibration tests conducted at the same scale in the two test areas are shown in Fig. 61.

When it became apparent, in the course of the equipment compressibility study, that maximum amplification (maximum gain on Attenuator 1) would be required for many tests, a technique was developed for calibrating (and using) the transducer in its finest displacement range (4 in. = 1.5 mils). The calibration-control circuit was used to set a scale of 4 in. = 3 mils on Attenuator 2 (in the vicinity of maximum gain); then, with the gain setting unchanged, the attenuator setting was simply changed from 2 to 1, thus doubling the amplification for a scale of 4 in. = 1.5 mils. In other words, the system was calibrated on Attenuator 2, and the test (either calibration or actual) was conducted on Attenuator 1. That the amplification on Attenuator 1 is precisely twice that on Attenuator 2 for the same gain setting (as it is designed to be) was verified at an amplification corresponding to Step A = 4 in. on Attenuator 1 (the limit of the linearity range). The gain setting was adjusted until Step A caused a galvanometer excursion of precisely 4.00 in., and the excursion was recorded. The attenuator setting was then changed from 1 to 2, and the new galvanometer excursion was recorded. In three such evaluations, conducted on different days, the ratio of galvanometer excursion on Attenuator 1 to that on Attenuator 2 varied from 1.99 to 2.02.

TRANSDUCER CALIBRATION LVDT NO. 0, COARSE RANGE CHANNEL 1 REPEATABILITY CHECK NOTE: TEST 1 WAS CONDUCTED UNDER THE DYNAPAK LOADER AND TEST 2 WAS CONDUCTED IN THE TEST AREA USED FOR LONG-DURATION TESTS	CORE MOVEMENT MILS	NET GALVANOMETER EXCURSION, IN ACTUAL	NET GALVANOMETER EXCURSION, IN NORMALIZED	CORE MOVEMENT MILS	NET GALVANOMETER EXCURSION, IN ACTUAL	NET GALVANOMETER EXCURSION, IN NORMALIZED		NET GALVANOMETER EXCURSION, IN ACTUAL	NET GALVANOMETER EXCURSION, IN NORMALIZED
	0	0.00	0.00	0	0.00	0.00			
	8	0.40	0.40	8	0.40	0.40			
	16	0.80	0.80	16	0.80	0.80			
	24	1.19	1.20	24	1.21	1.21			
	32	1.59	1.60	32	1.60	1.60			
	40	2.00	2.01	40	2.01	2.01			
	48	2.40	2.41	48	2.41	2.41			
	56	2.79	2.80	56	2.81	2.81			
	64	3.19	3.21	64	3.21	3.20			
	72	3.59	3.61	72	3.61	3.60			
	80	3.98	4.00	80	4.01	4.00			
	72	3.59	3.61	72	3.61	3.60			
	64	3.20	3.23	64	3.21	3.20			
	56	2.80	2.81	56	2.81	2.81			
	48	2.39	2.40	48	2.41	2.41			
	40	2.00	2.01	40	2.01	2.01			
	32	1.59	1.60	32	1.61	1.61			
	24	1.19	1.20	24	1.21	1.21			
	16	0.80	0.80	16	0.80	0.80			
	8	0.40	0.40	8	0.39	0.39			
	0	0.00	0.00	0	0.00	0.00			
	A	0.10	0.10	A	0.10	0.10			
	B	0.20	0.20	B	0.20	0.20			
	C	0.40	0.40	C	0.39	0.39			
	D	0.79	0.79	D	0.79	0.79			
	E	1.56	1.57	E	1.56	1.56			
	F	3.07	3.09	F	3.08	3.07			
CALIBRATION TEST NUMBER	1			2					
BEST LINEAR RELATION FOR DATA	3.98" = 80 MILS			4.01" = 80 MILS					
MAXIMUM DEVIATION FROM BEST LINEAR RELATION	0.01 INCH			0.01 INCH					
MECHANICAL-INPUT VALUES FOR CALIBRATION STEPS	F = 61.7 MILS			F = 61.4 MILS					
NORMALIZED RELATION	4.00" = 80 MILS			4.00" = 80 MILS					

a. DATA TABULATION



b. DATA PLOT

Fig. 61. Results of calibration tests for LVDT displacement transducer showing repeatability in spite of change in test area.

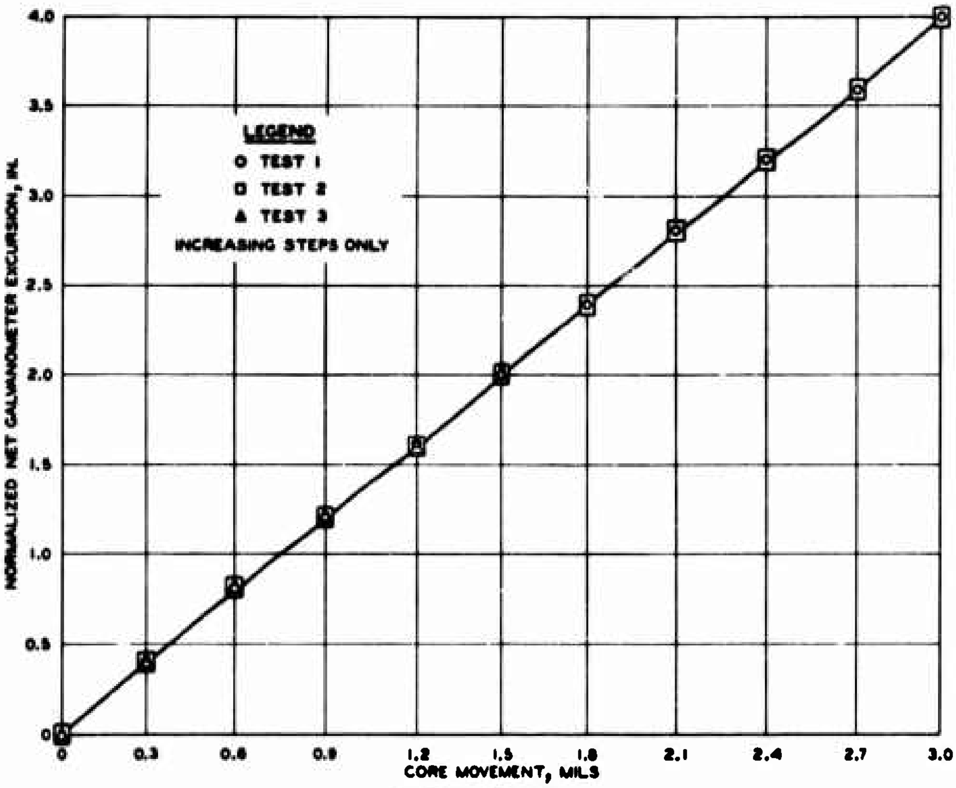
The results of a transducer-calibration test conducted at a scale of 4 in. = 1.5 mils with the technique described showed excellent agreement with the results of the two calibration tests (original and repeatability check) conducted at a scale of 4 in. = 3 mils (medium gain, Attenuator 1). The results of the three tests are presented in Fig. 62.

Drift. Information concerning drift in the output signal from the LVDT displacement transducer was obtained by recording the galvanometer excursion as a function of time several hours after a test was completed, with the equipment still assembled. Since the test results had clearly shown that the stress-strain characteristics of the sand used in the preliminary testing program were not time dependent (except, perhaps, in the fine displacement range--see results of Test No. A01A04, Figs. 122 and 123), it was anticipated that rebound creep in the specimen after loading would be negligible, especially several hours after the completion of the test. The transducer was evaluated in each of the three displacement ranges at scales of 4 in. = 60 mils, 4 in. = 15 mils, and 4 in. = 1.5 mils. The data were recorded over a period of 2 hr, at 15-min intervals.

The amount of drift observed was a function of the displacement range investigated. In both the coarse and medium ranges, the drift from the initial position did not exceed 0.02 in. (of galvanometer excursion). In the fine displacement range, the drift from the initial position over a 2-hr period was found to be 0.11, 0.07, and 0.07 in., in three investigations, each of which exceeds 0.04 in., or 1 percent of full scale. The drift did occur gradually, however, and there was no 45-min interval in which it exceeded 0.04 in. Consequently, when conducting long-duration

TRANSDUCER CALIBRATION LVDT NO. 0, FINE RANGE CHANNEL 1 REPEATABILITY CHECK NOTE: IN TEST 3, SYSTEM CALIBRATION WAS PERFORMED ON ATTENUATOR 2 AND TRANSDUCER CALIBRATION ON ATTENUATOR 1	CORE MOVEMENT, MILS	NET GALVANOMETER EXCURSION, IN		CORE MOVEMENT, MILS	NET GALVANOMETER EXCURSION, IN		CORE MOVEMENT, MILS	NET GALVANOMETER EXCURSION, IN	
		ACTUAL	NORMALIZED		ACTUAL	NORMALIZED		ACTUAL	NORMALIZED
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.30	0.39	0.39	0.30	0.40	0.40	0.30	0.83	0.41
	0.60	0.80	0.81	0.60	0.81	0.81	0.60	1.64	0.81
	0.90	1.20	1.21	0.90	1.21	1.20	0.90	2.45	1.21
	1.20	1.60	1.62	1.20	1.61	1.60	1.20	3.23	1.60
	1.50	1.99	2.01	1.50	2.01	2.00	1.50	4.04	2.00
	1.80	2.37	2.39	1.80	2.40	2.39	1.20	3.22	1.59
	2.10	2.78	2.81	2.10	2.81	2.80	0.90	2.42	1.20
	2.40	3.17	3.20	2.40	3.21	3.19	0.60	1.61	0.80
	2.70	3.58	3.60	2.70	3.61	3.59	0.30	0.79	0.39
	3.00	3.98	3.99	3.00	4.01	3.99	0.00	0.00	0.00
	2.70	3.58	3.60	2.70	3.61	3.59			
	2.40	3.17	3.20	2.40	3.21	3.19			
	2.10	2.77	2.80	2.10	2.81	2.80			
	1.80	2.38	2.40	1.80	2.40	2.39			
	1.50	1.99	2.01	1.50	2.00	1.99			
	1.20	1.59	1.61	1.20	1.61	1.60			
	0.90	1.19	1.20	0.90	1.21	1.20			
	0.60	0.79	0.80	0.60	0.81	0.81			
	0.30	0.40	0.40	0.30	0.40	0.40			
	0.00	0.00	0.00	0.00	0.00	0.00			
	A	2.59	2.61	A	2.61	2.60	A	2.64 (ATT 2)	2.60
CALIBRATION TEST NUMBER	1			2			3		
BEST LINEAR RELATION FOR DATA	3.99" = 3 MILS			4.02" = 3 MILS			4.05" = 1.5 MILS		
MAXIMUM DEVIATION FROM BEST LINEAR RELATION	0.02 INCH			0.01 INCH			0.02 INCH		
MECHANICAL-INPUT VALUES FOR CALIBRATION STEPS	A = 1.96 MILS			A = 1.96 MILS			A = 1.96 MILS		
NORMALIZED RELATION	4.00" = 3 MILS			4.00" = 3 MILS			4.00" = 3 MILS		

a. DATA TABULATION



b. DATA PLOT

Fig. 62. Results of calibration tests for LVDT displacement transducer showing repeatability in spite of change in calibration technique.

tests in the fine displacement range, it is advisable to limit the total duration of the test to 45 min.

It is important to note that even if the observed drift in the fine displacement range did not result from rebound creep in the specimen, a change of 0.11 in. in galvanometer excursion at a scale of 4 in. = 1.5 mils corresponds to a change in the relative positions of the core and coils of only 40 μin., or 0.04 mil (approximately). If the change in temperature of the 10-in.-long stainless-steel core rod during the 2-hr drift investigation was only 0.2 °F, the position of the core relative to that of the coils would have changed by that much. In view of this, it is surprising that the drift was not greater. Apparently, the thermal mass of the pressure fluid and the metal components surrounding it, when coupled with the controlled-temperature environment of the laboratory, is sufficient to keep the core rod at an essentially constant temperature for a period as long as 2 hr.

Frequency Response. Although the frequency-response characteristics of the LVDT displacement transducer could not be determined directly with available equipment and instrumentation (since the LVDT was the fastest responding displacement transducer available for the displacement range in which it is used in conjunction with the one-dimensional compression device), there is some indication from the data obtained during the actual-test phase of the evaluation program (Phase III) that they are satisfactory for the conditions of interest.

One indication of the satisfactoriness of the frequency-response characteristics of the LVDT displacement transducer can be obtained by comparing the LVDT-generated signal on the oscillograph record

from any of the short-duration tests in the preliminary testing program with the signal generated by either of the two pressure transducers used (see Fig. 47, for example). In none of the five short-duration tests conducted was there any evidence of a time lag in the response of the LVDT transducer.

Another indication that the frequency-response characteristics of the LVDT displacement transducer are satisfactory for the conditions of interest is provided by the stress-strain data from the various short-duration tests conducted (see Appendix B). Compare, for example, the stress-strain data for the fastest and slowest tests in the series (Figs. 125 and 131, respectively). In spite of the fact that the effective rise time was approximately 4 msec in one test and approximately 20 msec in the other, the response characteristics of the two specimens appear to be very nearly the same ($\pm$2-1/2 percent from a mean curve). Especially significant is the fact that the value of strain determined for any given value of stress in the faster test was actually greater than the value of strain for the corresponding value of stress in the slower test.

The stress-strain relations shown in Appendix B were obtained by drawing smooth curves through the experimental data points (see final portion of Section 4.1). The actual experimental data points for the fastest and the slowest tests in the series are shown in Fig. 63. (The apparent "scatter" during loading represents actual behavior during oscillations--see Section 4.3--and not experimental scatter of the data.) Even for the original data, which reflect differences in test details (such as oscillations), the agreement is quite good.

Although there is the possibility that the agreement indicated

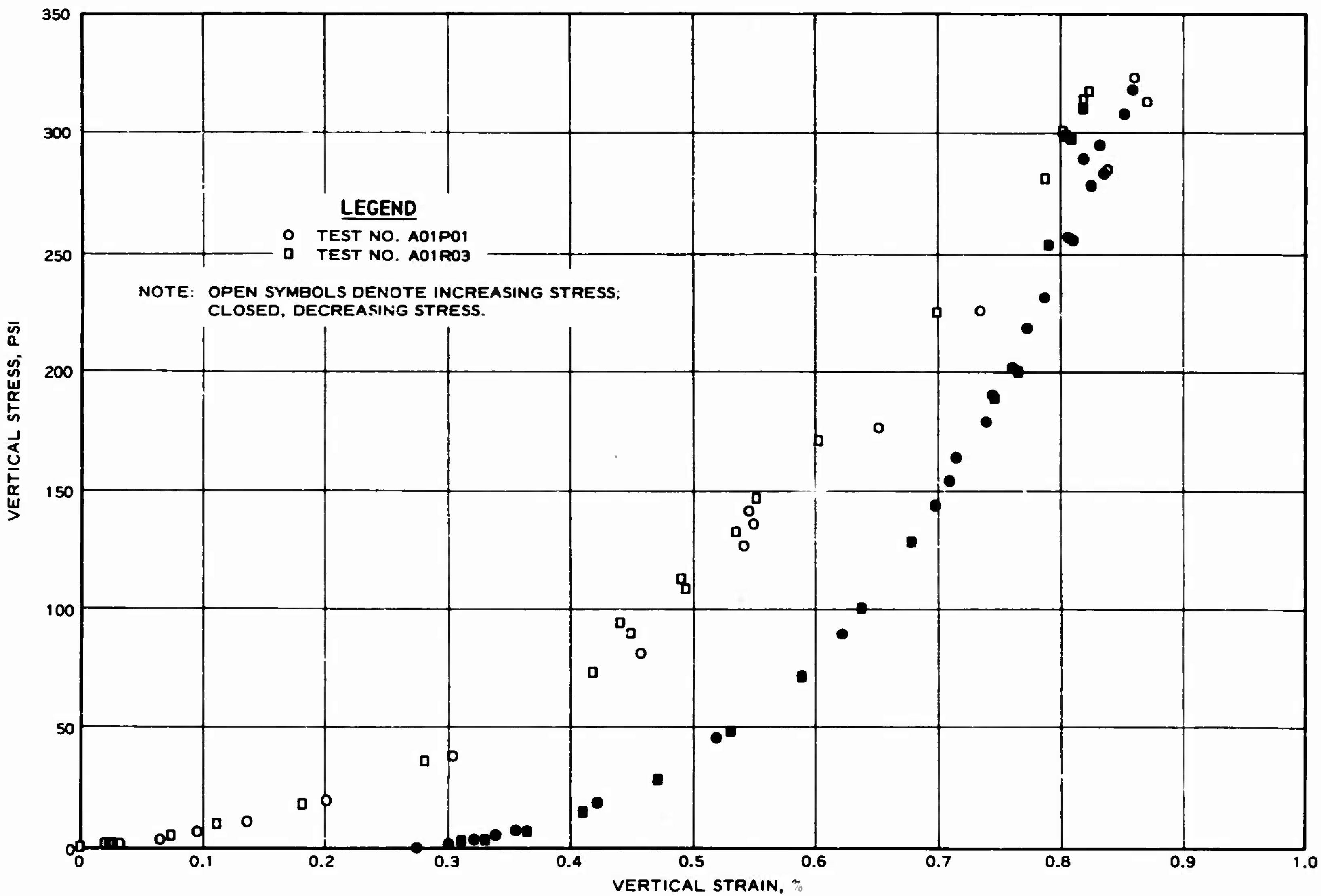


Fig. 63. Experimental data points for fastest and slowest short-duration tests in program.

results from a cancellation of errors, and that there is in fact a time lag in the LVDT response during the faster tests that exceeds 5 percent, it is more likely that the frequency-response characteristics of the LVDT are satisfactory, as predicted (see Section A.4), and that the spread in the data results from experimental error (see Section 4.6) and differences in the specimens tested. There is certainly no evidence to indicate any significant time effects in the response of the LVDT transducer.

Resolution. Resolution of the LVDT displacement transducer, as specified by the manufacturer, is infinite, indicating that there are no limitations in the transducer itself. With the $\pm$60-mil units used, it has been possible to resolve 0.0075 mil at the maximum gain setting on Attenuator 1; with the $\pm$300-mil units, it should be possible to measure surface displacements as large as 0.6 in., corresponding to a specimen strain of nearly 25 percent for the large (2-1/2-in.-thick) soil specimens. Clearly, any displacement of interest can be recorded with the units available with the existing amplifier-recorder system.

Other Evaluation. It was anticipated that the inductive nature of the LVDT transduction circuit would make this transducer particularly susceptible to changes in the magnetic conditions in its environment. It was for this reason that the LVDT core rod was originally made of a nonmagnetic material (see Section 3.6), and it was for this reason that all transducer calibrations were conducted in place, with the same proximity of the various, massive, metallic equipment components as during an actual test. It was also for this reason that a magnetic shield was specified for each set of coils. In addition to these precautions, a small evaluation program was conducted to determine the extent of the effect of several

typical changes in the environmental magnetic conditions on the behavior of the LVDT transducer.

The results of the evaluation program demonstrated quite clearly that the LVDT is well shielded against changes in the magnetic conditions in its environment. Neither small changes in its immediate environment nor large changes in its general (but not immediate) environment produced a noticeable change in its behavior (i.e., in the displacement-equivalent values determined for the calibration steps). The fact that the results of calibration tests conducted under the Dynapak loader agreed with the results of calibration tests conducted in the test area used for long-duration tests has already been mentioned. When the null position was raised 1/2 in., thereby moving the core closer to the top of the core housing, there was no change in the LVDT behavior. When the core housing was moved up and down 0.1 in. (the position of the core and coils remaining unchanged) to simulate relative motion between the housing and the core during a test, there was no noticeable change in galvanometer excursion. Similarly, with the position of the core and coils of LVDT No. 0 unchanged, neither operation of LVDT No. 2 nor removal of the bleed screw from the core housing for LVDT No. 0 produced a noticeable change in the galvanometer excursion for LVDT No. 0 in any of the three displacement ranges.

As one might expect, large or significant changes in the immediate environment of the LVDT did cause some change in its behavior. The use of a stainless-steel instead of a Plexiglas core rod resulted in an increase of approximately 2 percent in the output of the transducer, presumably as a result of the additional magnetic coupling provided by the

steel rod. Fortunately, the additional coupling did not adversely affect the linearity of the transducer. When the LVDT transducer was calibrated in a standard micrometer stand, removed from the device and with no core housing between the core and the coils, the output of the LVDT was found to be approximately 10 percent less than when it was calibrated in place. This difference also presumably results from a difference in the magnetic coupling in the two configurations.

Several other observations were made in connection with the behavior of the LVDT displacement transducer. The effects of temperature change and flexibility of the micrometer support system have already been mentioned. The presence of moisture in the vicinity of the LVDT coils affects its behavior, perhaps because the leads are not waterproofed. The presence of moisture in the vicinity of the core, on the other hand, has no effect on the behavior of the LVDT. When the transducer was calibrated with the fluid chamber filled with water, the results were no different from those obtained when the fluid chamber contained only air.

The mechanical coupling between the LVDT disc and the soil specimen was found to be satisfactory. When the technique currently in use for equipment assembly was first evaluated, coupling between the disc and a loose sand specimen was observed visually (Section 4.2). Later in the facility-evaluation program, a similar observation was made in conjunction with a dense sand specimen. Furthermore, in contrast with the mismatch difficulties encountered at the steel specimen-soil container interface and at the soil container-lower assembly container plate interface during the equipment-compressibility study (Section 4.4), no mismatch was found either at the LVDT disc-steel specimen interface or at the LVDT

disc-soil chamber interface. A comparison of the results of Test Nos. 25 and 27 in the equipment-compressibility study demonstrates this quite clearly (Fig. 64). The two tests were identical in all but one respect; in Test No. 27, the core rod for LVDT No. 4 was threaded into a hole (specifically machined for the purpose) in the base of the soil chamber, whereas, in Test No. 25, the core rod for LVDT No. 4 was attached to a disc which was seated on the base of the soil chamber in the ordinary manner. That the two tests were indeed identical is verified by the response of LVDT No. 0 (for which a disc was used in both tests). The absence of a mismatch at the interface between the base of the LVDT disc and its supporting surface--and, hence, the assurance of a satisfactory coupling between the disc and its supporting surface--appears to be the result of the limited contact area (less than 3 sq in.) at the interface.

4.5.4 Other Measurements

In addition to the two key measurements and the amplifier-recorder system, which are required for the successful operation of the one-dimensional compression device, the measurement system also contains several other measurements, which were considered to be desirable and were incorporated into the overall configuration of the device (see Section 3.6). Because these measurements are of secondary importance, in that the device can be used to determine the one-dimensional compression characteristics of soil specimens without them, the effort devoted to their evaluation in the facility-evaluation program was somewhat limited. It was anticipated that the advantages and limitations of these additional measurements would be studied further as the need arose in each case.

Lateral Stress in the Specimen. A photograph of the two types

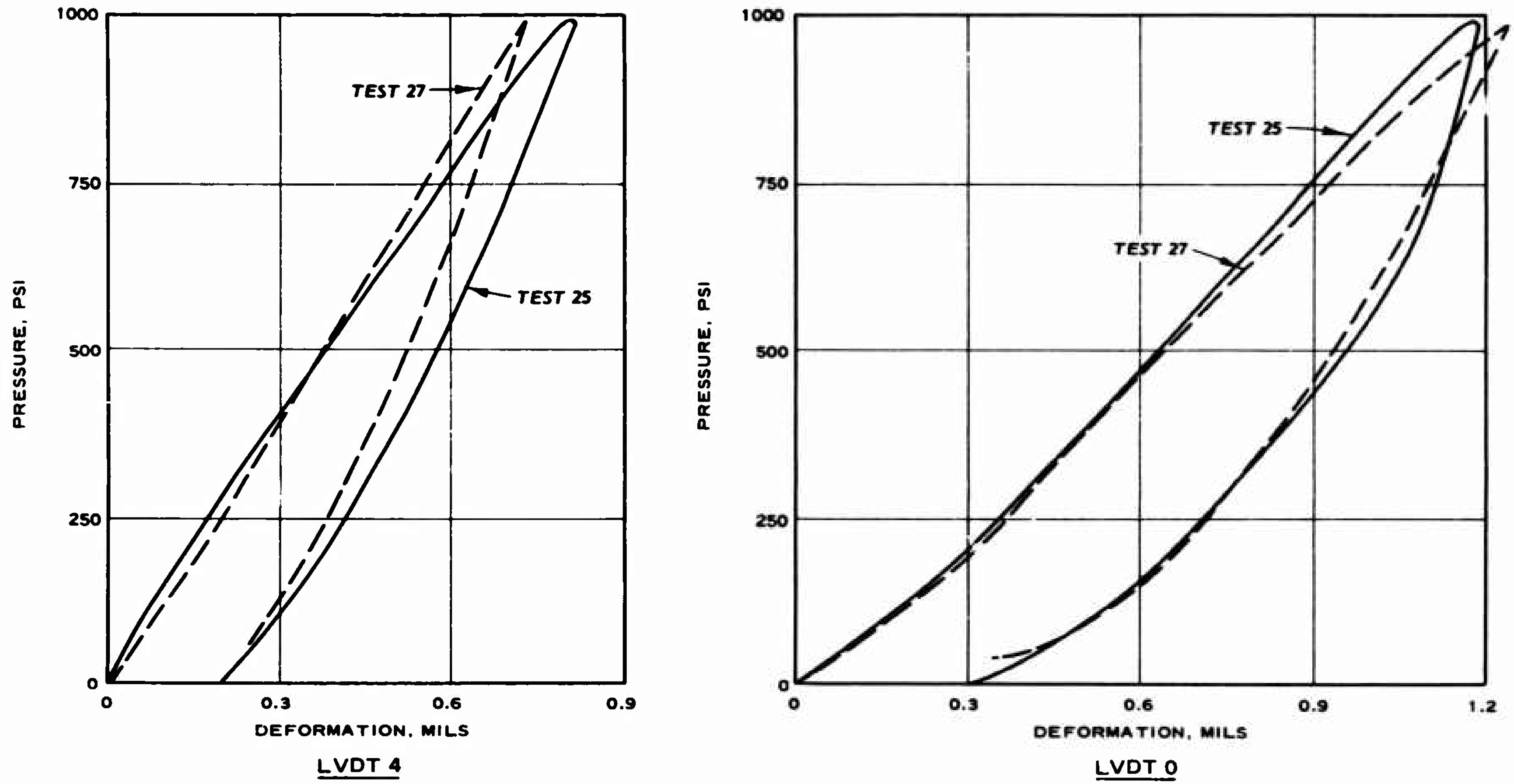
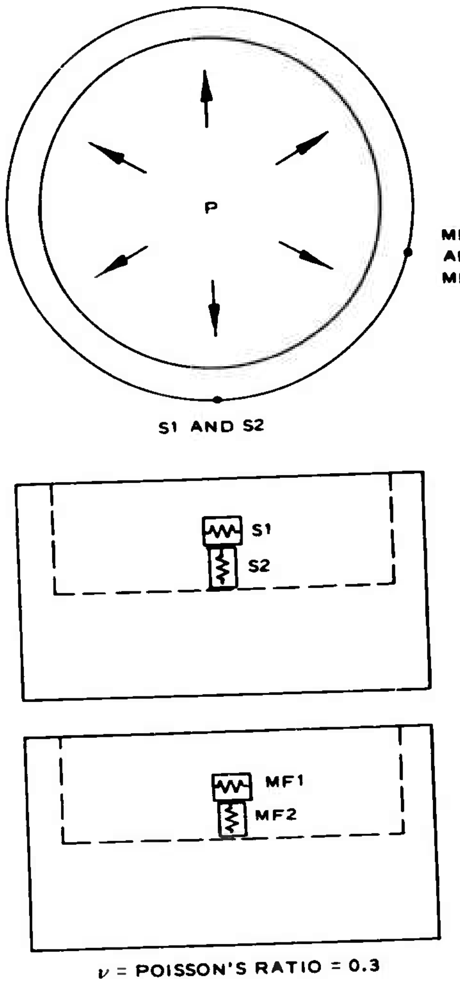


Fig. 64. Results of two equipment-compressibility tests demonstrating the absence of a mismatch at the LVDT disc-soil chamber interface.

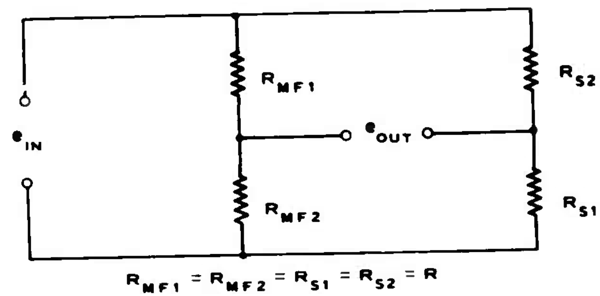
of strain-gage elements which were bonded to the outside periphery of the small soil container (to form a transducer for the determination of the lateral stress in the soil specimen) is shown in Fig. 28. At first, only the two metal-foil elements were bonded to the soil container; however, the sensitivity of the metal-foil elements was found to be inadequate, and the two semiconductor elements were added. Schematic drawings depicting the mechanical and electrical operation of the transducer formed by all four of the elements are shown in Fig. 65.

If the soil container were an axially infinite elastic cylinder, the relationship between the lateral stress or pressure on the inside wall of the cylinder and the output voltage of the transducer shown in Fig. 65 would be linear. With atmospheric pressure acting on both cylindrical surfaces, there would be essentially no output voltage, since the resistance values of all four resistors are nearly equal. As the lateral stress or pressure inside the cylinder was increased, the wall would deform, and the circumferential strain at its outside periphery would be proportional to the lateral stress or pressure that caused it (Section A.3). The change in circumferential strain would, in turn, create an output voltage from the transducer which would be linearly related to it (Fig. 65b).

Although a linear relationship between lateral stress or pressure and output voltage was not expected for the soil container, which differs from an axially infinite elastic cylinder in that wall expansion is restricted by a 1-in.-thick-base end boundary, it was anticipated that a more or less fixed (in the sense of repeatable), smooth, nonlinear relationship would be observed. This did not prove to be the case with the



a. MECHANICAL OPERATION



$$\frac{\Delta R_{MF1}}{R_{MF1}} = (K_g)_{MF1} \frac{\Delta L_{MF1}}{L_{MF1}} = 2.1 \frac{\Delta L_{MF1}}{L_{MF1}} = 2.1\, \epsilon_c$$

$$\frac{\Delta R_{MF2}}{R_{MF2}} = (K_g)_{MF2} \frac{\Delta L_{MF2}}{L_{MF2}} = 2.1 \frac{\Delta L_{MF2}}{L_{MF2}} = -2.1\, \nu\epsilon_c$$

$$\frac{\Delta R_{S1}}{R_{S1}} = (K_g)_{S1} \frac{\Delta L_{S1}}{L_{S1}} = 58 \frac{\Delta L_{S1}}{L_{S1}} = 58\, \epsilon_c$$

$$\frac{\Delta R_{S2}}{R_{S2}} = (K_g)_{S2} \frac{\Delta L_{S2}}{L_{S2}} = 58 \frac{\Delta L_{S2}}{L_{S2}} = -58\, \nu\epsilon_c$$

$$\frac{e_{OUT}}{e_{IN}} = \frac{\Delta R_{MF1} - \Delta R_{MF2} + \Delta R_{S1} - \Delta R_{S2}}{4R}$$

$$\frac{e_{OUT}}{e_{IN}} = \frac{(58 + 2.1)\, \epsilon_c + (58 + 2.1)\,(0.3)\, \epsilon_c}{4} = 19.5\, \epsilon_c$$

b. ELECTRICAL OPERATION

Fig. 65. Schematic drawing depicting operation of strain-gage lateral-stress transducer.

device assembled in the original auxiliary configuration (Fig. 17). The output voltage, as reflected by the change in galvanometer excursion for fixed amplification settings, changed erratically as pressure in the soil chamber was increased. (The soil chamber was filled with water instead of soil for these tests.)

When an investigation was conducted to determine the cause of the erratic behavior, it was found that an important source of strain in the soil-container wall had been neglected in the calibration of the transducer (Fig. 65b), i.e., the strain which results from initial tightening of the assembly bolts. When the device is assembled in the original auxiliary configuration and pressurized, the principal force is resisted in large part by relaxation of the initial compression in the device, the compression resulting from tightening of the assembly bolts. Consequently, although the increase in pressure on the soil-chamber wall may cause the circumferential strain-gage elements to expand and the temperature-compensation, axial strain-gage elements to contract, as anticipated, the axial-compression relaxation in the soil-container wall has the opposite effect, and the response of the transducer appears erratic as one of the effects or the other predominates.

An attempt was made to improve the performance of the transducer by replacing the temperature-compensation elements in the circuit with standard, unbonded resistance elements (not attached to the device). However, the resulting transduction circuit was highly unstable, in that the output was subject to a great deal of drift in a short period of time and was very sensitive to temperature change, and it could not be used. (The transduction circuit shown in Fig. 65b, on the other hand, had been

found to be very stable.) Since it was apparent that the strain-gage transducer could not be used to determine the lateral stress in the specimen with the device assembled in the auxiliary configuration, and since it was considered unlikely that such a measurement could be made successfully during the short-duration tests conducted with the device in the principal configuration (because of inertial stresses in the massive wall), plans for the inclusion of a lateral stress transducer in the measurement system were abandoned.

The tests described above were conducted very early in the facility-evaluation program (during the failure-leakage evaluation tests). Since the lateral-stress measurement was not one of the key measurements, there was no consideration given to modifying the auxiliary configuration to permit such a measurement to be made. However, later in the facility-evaluation program, when the results of the equipment-compressibility study had pointed to the need for a modified auxiliary configuration for other reasons (Section 4.4), use of the strain-gage transducer on the outside periphery of the soil container to determine the lateral stress in the specimen was reconsidered. It was anticipated that since the initial compression in the device is not relieved as the chamber pressure is increased, when the device is assembled in the modified auxiliary configuration, the performance of the transducer would be greatly improved over that observed earlier, when the device was assembled in the original auxiliary configuration.

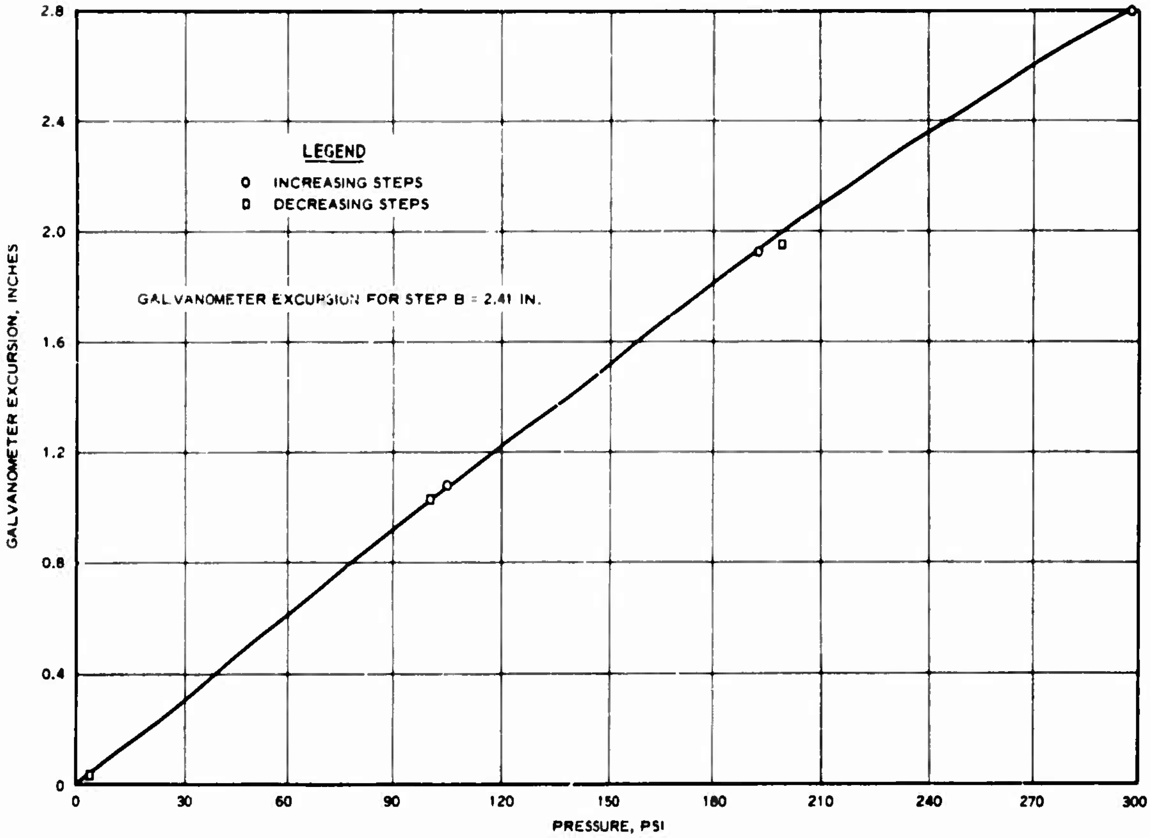
In order to provide experimental evidence in support of this contention, a test was conducted with the equipment in the original principal configuration, where the initial compression in the device also is not

relieved as the chamber pressure is increased. The results of this test (Fig. 66a), in which the fluid and soil chambers were pressurized in three 100-psi increments, clearly show that a definite relationship exists between the pressure in the soil chamber and the output of the transducer. Furthermore, the relationship appears to be quite reasonable, as evidenced by the magnitude of the strains measured (Fig. 66b).

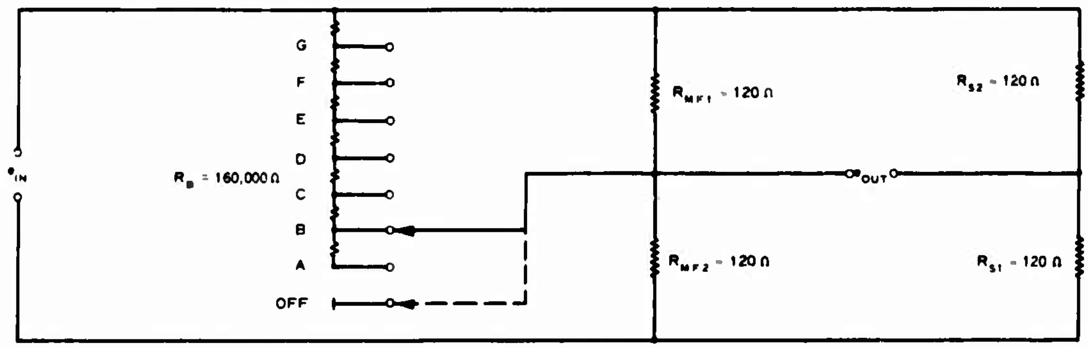
There has not yet been an opportunity to bond semiconductor strain-gage elements to either of the single-piece soil container-lower assembly container plates. Consequently, although it appears that it will be possible to use a strain-gage transducer (probably consisting of three pairs of semiconductor elements equally spaced at 120-deg intervals on the outside surface of the soil-container wall) to determine the lateral stress in a soil specimen during a one-dimensional compression test, this capability has not yet been demonstrated.

Surface Displacements at Several Locations. Four LVDT displacement transducers--one for the key displacement measurement (LVDT No. 0) at the center of the device and three others at radial distances of 2, 3, and 4 in. from the center (LVDT Nos. 2, 3, and 4)--were installed in the device. All four transducer units were of the same type, and only one, LVDT No. 0, was subjected to a fairly intensive evaluation (see discussion above). It was assumed that the performance characteristics of all four units would be the same.

A photograph of one of the LVDT displacement transducers is shown in Fig. 28. Schematic drawings depicting the mechanical and electrical operation of the transducer are shown in Fig. 56, and a schematic



a. RELATIONSHIP OBSERVED BETWEEN GALVANOMETER EXCURSION AND SOIL-CHAMBER PRESSURE



$$R_{MF1} = R_{MF2} = R_{S2} = R_{S1} = R$$

$$\left(\frac{e_{OUT}}{e_{IN}}\right)_{STEP\ B} = \frac{1}{4}\frac{R}{R_B} = \left(\frac{1}{4}\right)\left(\frac{120}{160{,}000}\right) = 0.188 \times 10^{-3}$$

$$(\epsilon_c)_{STEP\ B} = \left(\frac{1}{19.5}\right)\left(\frac{e_{OUT}}{e_{IN}}\right)_{STEP\ B} = \left(\frac{1}{19.5}\right)\left(0.188 \times 10^{-3}\right) = 9.64 \times 10^{-6}$$

$$\text{SCALE FOR TEST} = \frac{9.64 \times 10^{-6}}{2.41} = 4 \times 10^{-6} \text{ STRAIN PER INCH OF GALVANOMETER EXCURSION}$$

@ 300 PSI: $(\epsilon_c)_{MEASURED} = (4 \times 10^{-6})(2.8) = 11$ μIN./IN.

$(\epsilon_c)_{PREDICTED} = 11$ μIN./IN. (SECTION A.3)

b. COMPARISON OF MEASURED AND PREDICTED CIRCUMFERENTIAL STRAIN

Fig. 66. Results of evaluation test on strain-gage lateral-stress transducer.

drawing showing the modified transduction circuit used for the LVDT's is shown in Fig. 57.

Although the sidewall-friction study mentioned in Chapter 3 has yet to be conducted, the results of the actual-test phase of the facility-evaluation program provide some indication of the effect of sidewall friction in the fluid-loading-type one-dimensional compression device, and the extent of the effect. In all but one of the tests conducted, the initial relative density of the sand used was approximately 93 percent, and the peak strain reached (at 300 psi) was in the vicinity of 0.8 or 0.9 percent. For these conditions, the effect of sidewall friction was very small. The four stress-strain curves obtained for the test in which the effect appeared to be greatest, Test No. A01P04, are shown in Fig. 67. Clearly, any effect of sidewall friction on LVDT Nos. 0, 2, and 3 is within the scatter of the data. The same may be true about LVDT No. 4, although the slightly stiffer response measured by this transducer may actually represent an effect of sidewall friction. In either case, the effect of sidewall friction is small.

One test, Test No. A01A03, was conducted with the sand in a very loose initial condition. The results of this test, shown in Fig. 121, were very similar to those of Test No. A01P04 except that the stiffer response measured by LVDT No. 4 was more pronounced in Test No. A01A03. In spite of the fact that the portion of the specimen nearest the wall seems to have been stiffened approximately 10 percent by sidewall friction, the rest of the specimen appears to have been unaffected.

The very limited amount of data available indicates that there is some sidewall friction, that the sidewall friction has a noticeable

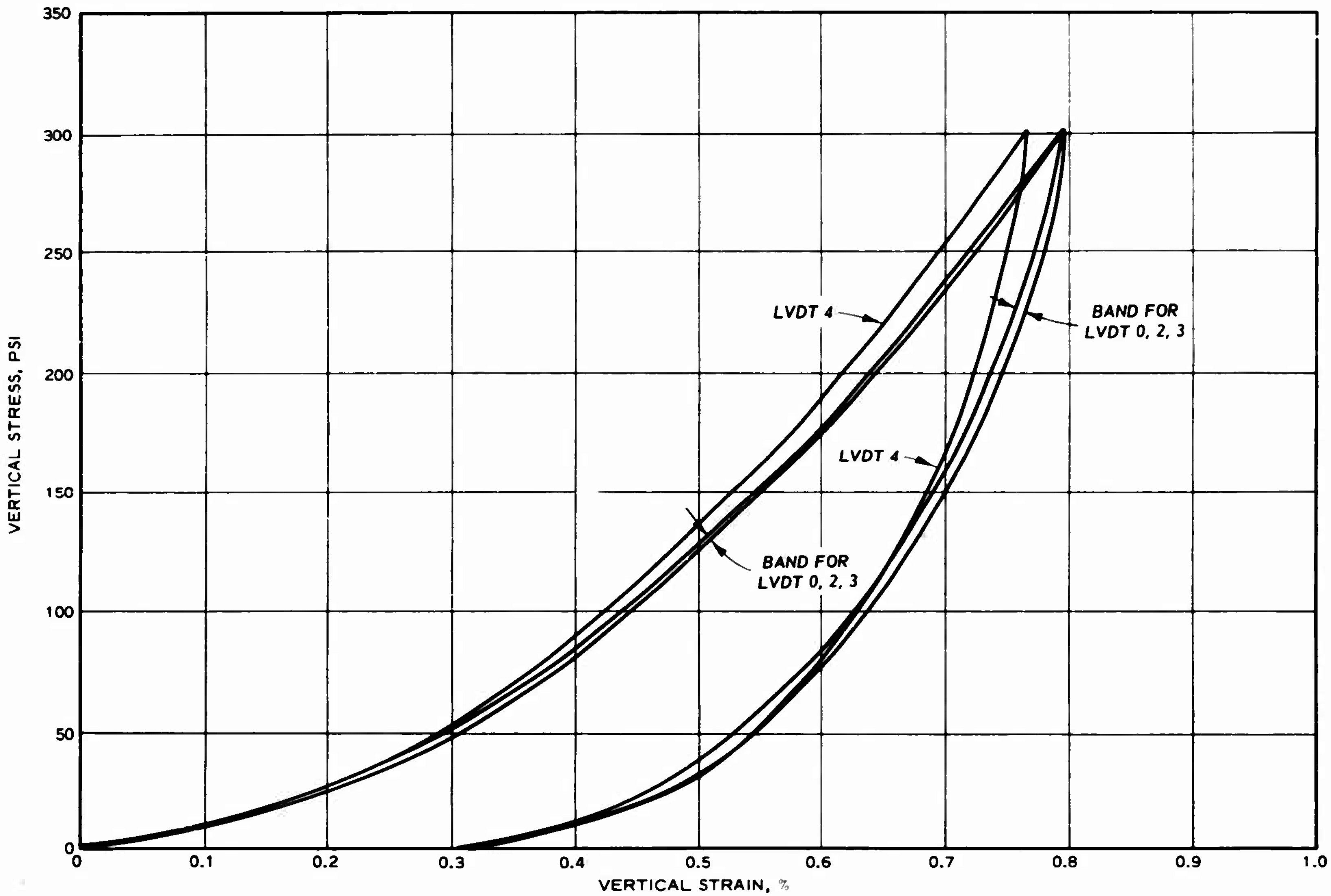


Fig. 67. Effect of sidewall friction on dense sand specimen.

effect on the response of the specimen nearest the wall, and that the magnitude of the effect (on this portion of the specimen, at least) increases with increasing surface displacement. Although there are no data to support it, there is every reason to believe that ever-increasing portions of the specimen will become affected as the magnitude of the surface displacement continues to increase. A 2-in.-diam disc (for the displacement sensor) at the center of a 10-in.-diam, 2-1/2-in.-thick specimen will probably be unaffected by sidewall friction for nearly all specimens of interest. A 2-in.-diam disc at the center of a 4-in.-diam, 1-in.-thick specimen, on the other hand, may be affected by sidewall friction for initially loose or soft specimens (i.e., those for which peak strains reach or exceed 5 percent).

The capability for studying sidewall-friction effects clearly exists. It is anticipated that this capability will be used to provide, for the first time, important quantitative information concerning the effect of sidewall friction and the extent of the effect on specimens with various diameter-to-depth ratios.

Differential Pressure. A photograph of one of the differential pressure transducers selected for use (Section 3.6) is shown in Fig. 28. The mechanical operation of the transducer is depicted schematically in Fig. 68; its electrical operation is essentially the same as that of the flush-mounted pressure transducer (Fig. 49b).

The differential pressure transducer was used in only one of the actual tests in the preliminary testing program, Test No. A01A04. In this test, the pressure was first slowly increased to approximately 95 psi, where it was held for several minutes until the displacement transducer

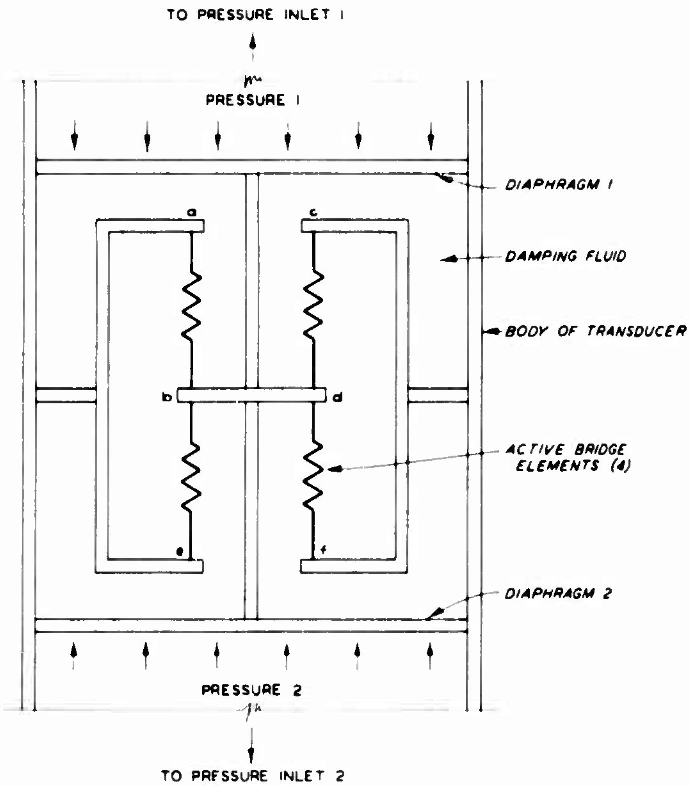


Fig. 68. Schematic drawing depicting mechanical operation of differential pressure transducer.

showed no further increase in surface displacement. (Although some creep did occur, it was very small.) After the LVDT had been renulled and its amplification settings readjusted for a finer scale, one side of the differential pressure transducer was sealed off from the load-application system, and the chamber pressure was increased by approximately 5 psi. Again the pressure was held constant, and again some creep was observed. The pressure was then decreased by approximately 5 psi, the amplification settings for the LVDT were readjusted to the original scale, the pressure on both faces of the differential transducer was equalized, and the chamber pressure was brought to zero.

The results of the test, shown in Figs. 122 and 123, demonstrated that the WES one-dimensional compression device can be used to study the behavior of a soil specimen subjected to a very small change in applied pressure, even if the initial pressure (relative to which the change is made) is high.

Pressure Near Center of Fluid Chamber. A photograph of the piezoelectric transducer selected to measure the pressure near the center of the fluid chamber is shown in Fig. 28. The nature of the installation used is shown in Fig. 15.

The capacity to convert pressure into a proportional electric charge is a property of the piezoelectric material from which the transducer is made. Although there is an electric potential associated with the charge developed by the piezoelectric material, this potential cannot be used to do any significant amount of work (such as driving a galvanometer) directly. The work would simply discharge the potential difference. Consequently, a charge amplifier is required to develop an output voltage

which is proportional to the charge developed by the transducer. The output voltage developed by the charge amplifier can be used directly with an oscilloscope, but it must be further amplified before it can be used to drive a galvanometer in a light-beam oscillograph (Fig. 30). The amplifier-recorder system through which the output voltage passes is shown schematically in Fig. 69.

Because the electric charge generated by the piezoelectric pressure transducer tends to leak off with time, the transducer cannot be used for long-duration tests. (Drift of the output signal generally becomes noticeable after approximately a second in most cases.) Consequently, it was not possible to calibrate this transducer, or to evaluate it, statically. Instead, the linearity and repeatability of the relationship between pressure and galvanometer excursion (and between pressure and electron-beam excursion, on the oscilloscope) were evaluated under rapidly changing pressure conditions. The device was assembled in the principal configuration with both the flush-mounted pressure transducer and the piezoelectric pressure transducer in position. A pressure pulse consisting of a rise time, hold time, and decay time of approximately 50 msec (each) was then applied by the Dynapak. With the known response of the flush-mounted transducer providing the pressure history, the response of the piezoelectric transducer was calibrated and evaluated for linearity. Additional tests were conducted tc afford an opportunity for evaluating the repeatability of the calibration. Because the test durations were not extremely short, it was anticipated that there would not be any important time effects in the response of the flush-mounted transducer, particularly since the design computations had indicated that there would not be any

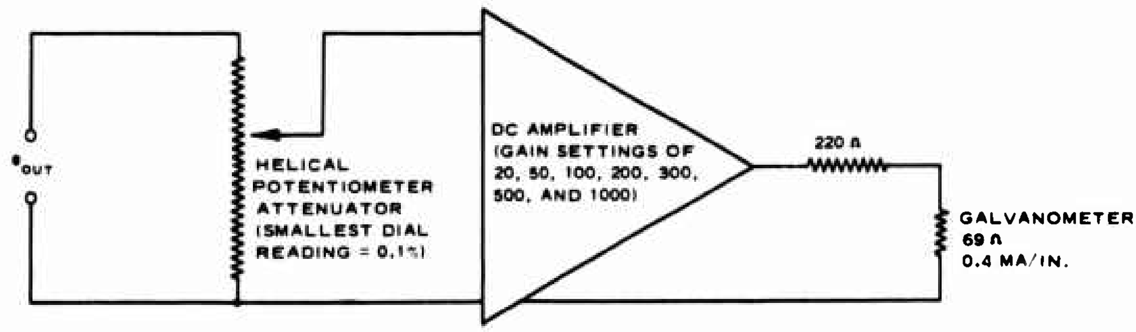


Fig. 69. Amplifier-recorder system for piezoelectric pressure transducer.

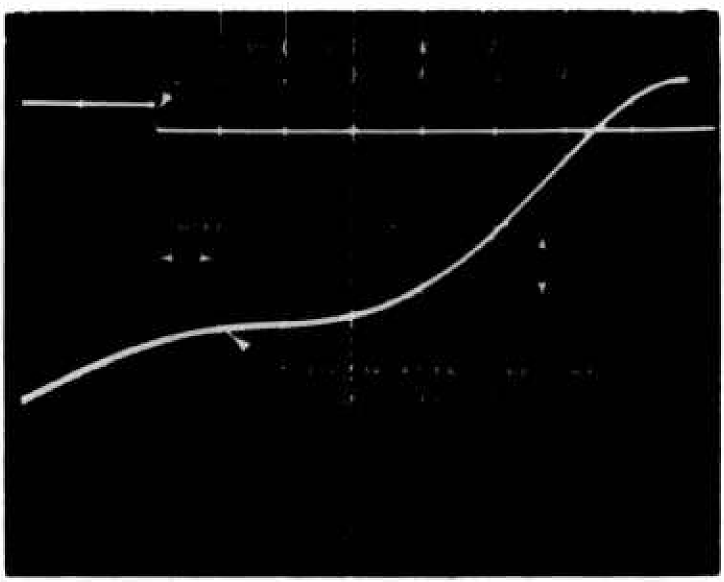


Fig. 70. Photograph of oscilloscope screen during fastest short-duration test showing absence of high-frequency components in pressure pulse.

important time effects even for far more rapid tests (Section A.4); in any case, the inclusion of a hold time in the programmed pressure pulse provided some assurance that at least one reading would not be influenced by time effects.

The results were very encouraging. The relationship between pressure and galvanometer excursion for the particular piezoelectric pressure transducer used was found to be both linear and repeatable to better than ± 1 percent for all tests. Also, charge leakage was found to be insignificant for all tests with a total duration of 1 sec or less. (None of the tests conducted with the equipment assembled in the principal configuration had a total duration much longer than 1 sec.) Although the output signal was observed to drift badly over a period of several seconds, the zero reading at the end of each pressure pulse was found to be very nearly equal (within 1 percent) to the zero reading prior to the pulse.

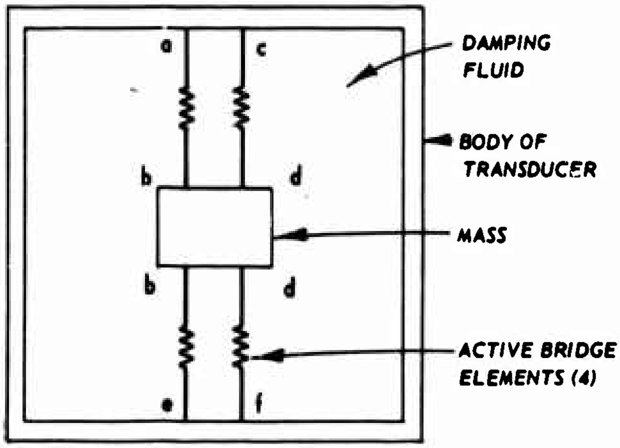
The piezoelectric pressure transducer, a transducer with excellent high-frequency response characteristics, was obtained principally for use in the facility-evaluation program (see Section 3.6), and it served its purpose quite well. It was used, as described earlier in this section, to evaluate the frequency-response characteristics of the flush-mounted pressure transducer and to demonstrate that the applied pressure was uniform across the entire specimen. It was also used in conjunction with the oscilloscope to show that there were no high-frequency components in the pressure pulse which might not have been discernible with the slower (relative to the oscilloscope) amplifier-recorder system ordinarily used. Fig. 70 shows a photograph of the oscilloscope screen made during the rise portion of Test No. A01P01, the test with the fastest rise time in the

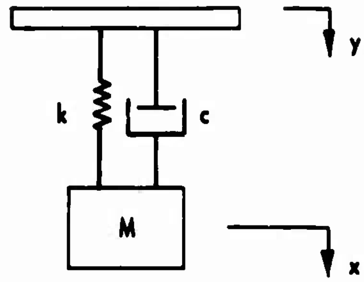
program. The photograph, which includes much of the rise portion of the pulse, clearly shows that there were no high-frequency components to the pressure pulse.

Since the frequency-response characteristics of the flush-mounted pressure transducer have been found to be quite satisfactory, it is anticipated that the piezoelectric transducer will not be required for use on a regular basis.

Relative Displacement Between LVDT Coils and Soil Container. An attempt was made to determine the relative displacement between the LVDT coils and the base of the soil container, and hence the magnitude of equipment compressibility, as a function of time during a short-duration test by measuring the acceleration of the LVDT coils and the soil container and double-integrating the two acceleration records obtained (see Section 3.6). A photograph of one of the accelerometer units used is shown in Fig. 28, and the nature of the installation selected can be seen in Fig. 14. The mechanical operation of the transducer is depicted schematically in Fig. 71; its electrical operation is essentially the same as that of the flush-mounted pressure transducer (Fig. 49b).

Mechanically, the strain-gage accelerometer used represents a damped, single-degree-of-freedom system, which is subjected to a base disturbance in the form of motion (rather than force). When the disturbance is sinusoidal, the steady-state response of the single-degree-of-freedom system is such that the relative displacement between the body of the accelerometer and the mass suspended in it (i.e., the change in the length of each active strain-gage element) is directly proportional to the input acceleration. Since the change in resistance of an active strain-gage





$$u = x - y \qquad \omega_n = \sqrt{k/M}$$

$$c = hc_{cr} = 2h\omega_n M$$

$$M\ddot{u} + c\dot{u} + ku = -M\ddot{y}$$

FOR A SINUSOIDAL DISTURBANCE:

$$y = y_0 \text{ SIN } \omega t$$

$$M\ddot{u} + c\dot{u} + ku = M\omega^2 y_0 \text{ SIN } \omega t$$

THE STEADY STATE SOLUTION:

$$u = u_0 \text{ SIN } (\omega t - \phi)$$

$$u_0 = \frac{(\omega/\omega_n)^2 y_0}{\sqrt{\left[1 - (\omega/\omega_n)^2\right]^2 + \left[2h(\omega/\omega_n)\right]^2}} = \frac{\omega^2 y_0}{\omega_n^2 \sqrt{(1-\beta^2)^2 + (2h\beta)^2}}$$

$$\phi = \text{TAN}^{-1}\left(\frac{2h\beta}{1-\beta^2}\right)$$

THEREFORE:

$$\left(\frac{\Delta L \text{ IN SPRING}}{\text{BASE ACCELERATION}}\right)_{MAX} = \frac{u_0}{\omega^2 y_0} = \frac{1}{\omega_n^2} \frac{1}{\sqrt{(1-\beta^2)^2 + (2h\beta)^2}}$$

$$\text{PHASE SHIFT} = \phi = \text{TAN}^{-1}\left(\frac{2h\beta}{1-\beta^2}\right)$$

Fig. 71. Schematic drawing depicting mechanical operation of acceleration transducer.

element is directly proportional to its change in length, and since the output voltage induced in a resistive bridge is directly proportional to the change in resistance of the active strain-gage elements, the transduction is linear.

When the input disturbance is complex and consists of an infinite series of harmonic components, two complications are introduced in the acceleration measurement. The constant of proportionality, relating the change in length of the active strain-gage elements to the input acceleration, is different for each harmonic component, and the amount of phase shift that occurs is different for each harmonic component. The effect of these differences is minimized when the single-degree-of-freedom system is 70 percent damped. It can be shown that, for such a system, the constant of proportionality is the same (within 1 percent) for all harmonic components with a frequency less than or equal to approximately 40 percent of the natural frequency of the accelerometer (Fig. 99), and the time lag (resulting from phase shift) is very nearly the same for all harmonic components with a frequency less than or equal to the natural frequency of the accelerometer, since the phase shift is directly proportional to frequency (Fig. 100). (Because the time lag is the same for all harmonic components, there is no phase distortion in the measured signal.)

Shortly after the decision had been made to incorporate the two accelerometers in the measurement system, the mismatch at the soil container-lower assembly container plate interface was found. The evaluation program for the two acceleration measurements was therefore postponed until the equipment-compressibility effect could be evaluated for the device assembled in the modified test configurations. When the magnitude of

the equipment compressibility was found to be greater than that thought to be desirable, it was decided to determine if the two accelerometers could in fact be used, as originally planned. However, because there was little difference found between the equipment compressibility measured during a short-duration test and that measured during a long-duration test (see Section 4.4), the success of the measurement was not considered to be as important a consideration as when the measurement was originally planned (see Section 3.6).

The first step in the evaluation program was to determine the range of accelerations likely to be encountered at the two locations of interest. After several accelerometers had been obtained (two in the ±50-g range and two in the ±15-g range) and calibrated by the simple 2-g turnover technique, the device was assembled in the principal configuration and placed under the Dynapak. Several different types of pressure pulses were applied, and the accelerations corresponding to each were measured. The results clearly showed that it would not be possible to use the available strain-gage accelerometers (or any other accelerometers) to determine the relative displacement between the LVDT coils and the base of the soil container-lower assembly container plate accurately. The equipment accelerations were too small and too erratic.

Three tests were conducted with an effective rise time of 3 msec, the fastest rise time permissible in the test program for the accuracy specified (see Section A.1), and the accelerations measured at each of the two locations varied from approximately 1 to approximately 3 g's. It is obviously not possible to preselect a good scale (i.e., one which will provide adequate resolution for the accuracy required) if there is an

uncertainty of 300 percent in the peak value anticipated. Furthermore, even if the peak acceleration could be predicted exactly, the resolution would still not be satisfactory for the small displacements anticipated, because the amplitude of the acceleration would be too small. Consider, for example, a test for which the peak acceleration will be 2 g's. Amplification settings corresponding to a scale of 2 in. = ± 2 g's are selected (recall that the total linearity range of the galvanometer is only 4 in.), and the test is conducted. If an error of only 0.02 in. is made in the zero reading, the displacement obtained by double integrating the acceleration record will be in error by approximately 0.4 mil after 10 msec. Since the peak relative displacement anticipated is approximately 0.25 mil at 300 psi (Section 4.4), this error is clearly not tolerable.

Fortunately, as mentioned above, when the modified device was evaluated for equipment compressibility, little difference was found between the equipment compressibility measured during a short-duration test and that measured during a long-duration test. It was anticipated that, under these conditions, it would be possible to use the results of a single short-duration equipment-compressibility test for correction of the specimen-deformation measurements obtained during all short-duration tests without introducing any error of consequence.

If, at some later time, it proves to be desirable to determine the relative displacement between the LVDT coils and the soil container-lower assembly container plate during a test, it is recommended that the measurement be made directly. One possible method is depicted schematically in Fig. 72. Because the motions are small, the slot at the base of the soil container-lower assembly container plate can be small.

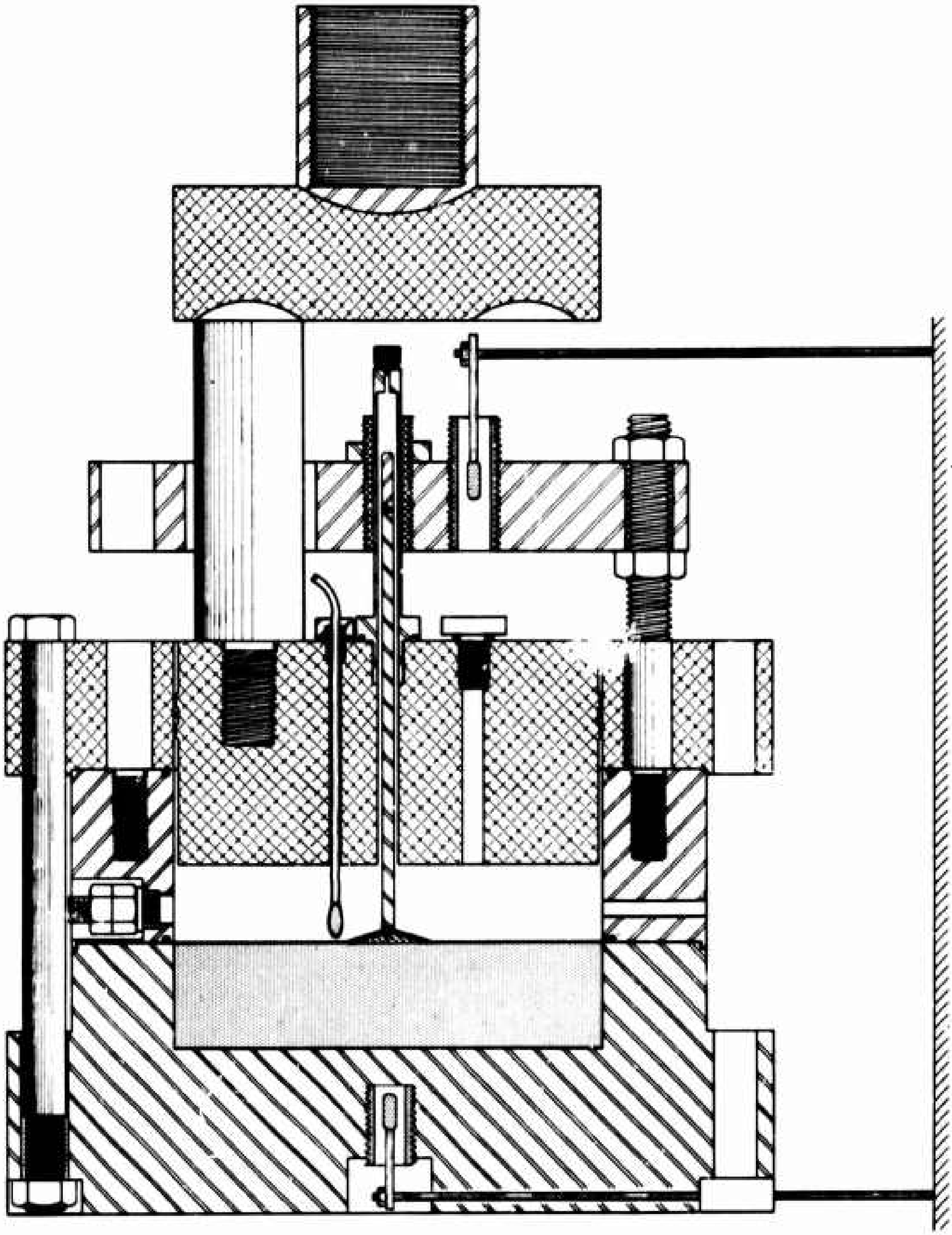


Fig. 72. Schematic drawing depicting possible configuration for direct measurement of equipment compressibility.

There will be no errors in the measurement resulting from shear and/or bending displacements in the cantilever support sections, since these sections will not undergo any motion and consequently will not be subjected to inertial loadings. In the configuration shown, the relative displacement can be obtained on the oscillograph record directly by electrically subtracting the output signals from the two LVDT's before they are returned to the amplifier.

4.6 Facility as a Whole

4.6.1 Experimental Accuracy

The principal purpose of the facility-evaluation program was to provide quantitative information, wherever possible, concerning the individual contributions to experimental error from the various sources within the overall test facility. The results of the program have been presented in varying degrees of detail in the earlier portions of this chapter. It is advantageous at this time to review the individual contributions in terms of the design groups with which they are most closely associated (see Chapter 3), and to reconsider them in the light of their cumulative effect on the experimental-accuracy capability of the facility as a whole.

Equipment Assembly. When the technique described earlier in this chapter is used for assembly and relocation of the equipment, the experimental error resulting from disturbance to the specimen in the soil chamber is negligible for all conditions of interest (Section 4.2). Even when the equipment is assembled routinely, the experimental error resulting from specimen disturbance is important only for soils which are highly

unstable, such as very loose sands, some types of loess, and perhaps highly sensitive or highly overconsolidated clays. When such specimens are disturbed, the structural configuration of the material--and, hence, the resistance of the material to an increase in load--is changed. Consequently, the strains measured after disturbance are not the same as the strains which would have been measured had the specimen not been disturbed. The error is systematic, and the direction of the error (and also its magnitude) depends on the particular type of specimen.

Specimen-Containment System. The principal source of experimental error in the specimen-containment system is sidewall friction (Section 3.3). The error is systematic in that the effect of sidewall friction is always to reduce the vertical strain in the specimen.

The magnitude of the sidewall-friction error is not yet known for all the conditions of interest, although it is anticipated that this information will become available in the near future when a comprehensive sidewall-friction study is conducted at WES. It does appear, however, from the limited amount of data already available (Section 4.5), that the magnitude of the sidewall-friction error is not small enough to be neglected in all cases. The error can probably be neglected for all 10-in.-diam specimens of interest provided that (1) the diameter of the LVDT disc used is no larger than the one used in the preliminary testing program (1-7/8 in.), and (2) the small soil chamber is used. (The large soil chamber can be used for the stiffer 10-in.-diam specimens, and probably should be, in order to minimize the effects of end disturbance which are particularly severe for a stiff specimen (Whitman and Clark, 1964).) Specimens less than 10 in. in diam, such as those in sampling tubes or

those prepared in rings outside the soil chamber, should certainly be as large in diameter as possible in order to minimize the effect of sidewall friction, and should probably be tested in the small soil chamber whenever possible.

Load-Application System. The only recognized source of experimental error in the load-application system is nonuniform loading.

The uniformity of the applied loading across the surface of the specimen was investigated during the preliminary testing program, and the results of the investigation indicate that the entire specimen surface is subjected to the same pressure at each instant of time (Section 4.5). Consequently, there is no experimental error from this source.

Uniformity of loading as a function of depth in the specimen can be held to the specified 1-percent value by proper selection of the effective rise time and the effective decay time for any given test (in accordance with Equation 2.1). The error from this source affects the accuracy of the pressure measurement in that the pressure measured above the specimen at any instant of time is not equal to the average stress in the specimen at that time. The direction of the error is random. The magnitude of the error can be computed from Equation 2.1 for any given pressure pulse actually obtained.

Load-Support System. Contributions to the experimental error from the load-support system stem principally from two sources, equipment compressibility and lateral straining of the soil-chamber wall.

If the specimen-deformation measurement is not corrected for equipment compressibility, the measured displacement and the computed strain are too large. The magnitude of the resulting systematic error

depends on the thickness of the specimen, the duration of the loading, and the stiffness of the specimen (Section 4.4) For a 1-in.-thick specimen, the equipment compressibility varies from approximately 0.5 μin. per psi for long-duration tests to approximately 0.75 μin. per psi for very short-duration tests. For a 2-1/2-in.-thick specimen, the equipment compressibility varies from approximately 0.33 μin. per psi for long-duration tests to approximately 0.6 μin. per psi for very short-duration tests. It should be noted that although the error in the surface-displacement measurement at any given pressure is very nearly the same for a 2-1/2-in.-thick specimen as for a 1-in.-thick specimen, the error in the computed strain is approximately 2-1/2 times less for the larger specimen.

If the specimen deformation measurement for any given test is corrected for equipment compressibility--either in accordance with the above relations, by predetermination (precalibration) under the same loading conditions as during the test (Section 3.6), or by direct measurement of the equipment compressibility during the test (final portion of Section 4.5)--the error in the measurement can be greatly reduced. When a correction is used, the direction of the experimental error becomes random. The magnitude of the error probably depends on the method used for determining the correction; however, it is believed that no matter which method is used, the error is less than 1 percent for all conditions of interest.

Although the lateral strains in the soil-container wall have not been measured, it can safely be assumed that they are at most equal to those predicted by theory for an axially infinite elastic cylinder

(Section A.3). (A single determination was made of the circumferential strain in the wall of the small soil container, with the device assembled in the original principal configuration. The results, shown in Fig. 66, indicate that the response of the wall is nearly that predicted for an axially infinite elastic cylinder.) Similarly, it is reasonable to assume that the lateral strains in a confining ring, which is used for specimens less than 10 in. in diam, are very nearly equal to those predicted by theory for an axially infinite elastic cylinder (Kane, Davisson, Olson, and Sinnamon, 1964). The experimental error which results from the lateral straining of the specimen is systematic in that the measured deformations are always too large.

If the value of Poisson's Ratio for the specimen is known, or if it can be estimated, the magnitude of the experimental error can be estimated for any given confining ring properties in accordance with the simplified method of analysis used in the design of the device (Section A.3). For a 10-in.-diam specimen, the magnitude of the error is clearly less than 1 percent for nearly all soils of interest; even if a soil were to be found with a constrained modulus between 50 and 200 ksi and a Poisson's Ratio approaching 0.5, the worst possible condition, the error still would not exceed 4 percent and would probably be much less than that (according to the method of analysis used--see Fig. 95). For a specimen less than 10 in. in diameter, the lateral specimen strain can effectively be eliminated by filling the volume of the soil chamber between the confining ring of the specimen and the soil-container wall with a material which has a Poisson's Ratio nearly equal to or greater than that of the specimen tested.

Measurement System. The measurement system from which the data are obtained contains many possible sources of experimental error. Those recognized and investigated in the facility-evaluation program include nonlinearity, nonrepeatability, drift, time effects, and resolution limitations, both in the two key-measurement transducers and in the amplifier-recorder system used in conjunction with these transducers (Section 4.5), and the mismatch at the LVDT disc-specimen surface interface. Experimental errors resulting from the indirect nature of the two key measurements have already been considered (nonuniform loading and equipment compressibility).

The experimental error which results from nonlinearities in the relationship between chamber pressure and galvanometer excursion for the flush-mounted-pressure-transducer signal is of the random type. Although the magnitude of the error was observed to be as large as 1 percent of the peak value, it is believed that the probable error does not exceed 0.75 percent. The same comments apply for the relationship between LVDT-core motion and galvanometer excursion for the LVDT-displacement-transducer signal.

The experimental error which results from the inability to obtain an exactly repeatable relationship between chamber pressure and galvanometer excursion for the flush-mounted-pressure-transducer signal is of the random type, and the magnitude of the probable error from this source is approximately 1 percent of the peak value (though it may be somewhat less than this). The same comments apply in connection with the LVDT transducer.

The experimental error which results from drift of the flush-mounted-pressure-transducer signal (caused by drift in the

amplifier-recorder system as well as by drift in the transducer itself) is of the random type, and the magnitude of the probable error from this source is 1 percent of the peak value. The same comments apply in connection with the LVDT transducer (provided the total duration of the test does not exceed 45 min when the LVDT is used in the fine displacement range).

The experimental error which results from limitations in the frequency-response characteristics of the two key-measurement transducers and the amplifier-recorder system is probably of the systematic type. The direction of the error is not known, since there is no convenient method available for independently evaluating the frequency-response characteristics of the LVDT transducer (Section 4.5). Nevertheless, it appears, both from the results of theoretical computations (Section A.4) and from the results of the preliminary testing program (Section 4.5), that the magnitude of the error probably does not exceed 2 percent of the peak value (of modulus), provided that the effective rise time and the effective decay time are not shorter than the values computed from Equation 2.1. Because the direction of the error is not known, it should be assumed to be random.

The experimental error which results from the inability to resolve small changes in galvanometer excursion is of the random type. The magnitude of the probable error from this source is 0.5 percent for the pressure measurement (the peak value of which can be predicted accurately) and 1 percent for the displacement measurement (provided that the peak value can be estimated within ± 30 percent prior to the test).

The experimental error which results from a mismatch at the

LVDT disc-specimen interface is systematic in that the measured displacement, which reflects not only the compressive response of the specimen but also the seating displacement of the LVDT disc against the specimen, is too large. It is believed, on the basis of several observations made during the facility-evaluation program (Section 4.5), that the magnitude of the error is small enough to be neglected for all soils of interest.

Test Facility. The experimental accuracy of the data obtained from a test conducted in the WES general-purpose, one-dimensional compression test facility depends on the cumulative effect of the various individual contributions to the experimental error for that test. It has been shown that the contributing factors from which these individual contributions stem include (1) specimen disturbance during equipment assembly, (2) sidewall friction, (3) nonuniform loading conditions, (4) equipment compressibility, (5) lateral specimen strain, (6) nonlinearity of transducer response, (7) nonrepeatability of transducer response, (8) drift in the transducer signal, (9) frequency-response limitations in transducer response, (10) signal-resolution limitations, and (11) mismatch at the (LVDT) disc-specimen interface. Of these, only factors (6), (7), and (10) can be considered to be fairly independent of the special conditions which characterize each individual test; the errors which stem from these three independent factors are of the random type, and their magnitude for any particular test depends principally on statistical considerations. The errors which stem from the other factors outlined depend, at least in part, on the special conditions which characterize each individual test. Specimen disturbance during equipment assembly depends on the sensitivity of the soil specimen; the magnitude of

the sidewall-friction effect depends on the diameter of the specimen and the stiffness of the soil specimen; nonuniform loading conditions are most severe for very short-duration loadings; the significance of equipment compressibility is directly related to the stiffness of the soil specimen; the magnitude of the lateral specimen strain depends on the Poisson's-Ratio value of the soil specimen; drift in the transducer signal depends on the duration of the test; frequency-response limitations in transducer response are most severe for very short-duration loadings, and mismatch at the disc-specimen interface depends on the nature of the soil specimen and the characteristics of its upper surface.

The large number and diverse nature of the contributing factors make it extremely difficult, if not impossible, to establish an experimental-accuracy capability for the test facility which could be considered to be applicable for all the conditions likely to be of interest. The statistical significance of the limited amount of pertinent data available from the facility-evaluation program is not nearly sufficient to justify the broad-based extrapolation required, in any case. It is possible, however, to obtain an indication of the experimental accuracy of the data obtained for any particular set of conditions. The particular set of conditions may be that which characterizes one particular test, or it may be that which characterizes some hypothetical situation which represents a large number of individual tests.

It is instructive to examine the experimental-accuracy capability of the test facility for two hypothetical situations of particular interest. One such situation, referred to herein as the routine test, is that which represents a large majority of the individual tests likely

to be conducted. There probably will be no attempt to evaluate the effect of the various factors outlined above on the accuracy of the data obtained. Consequently, both the vertical-stress and the vertical-strain values determined from the data obtained will be in error; the magnitude of the error in any vertical-stress value will depend on the cumulative effect of the individual contributions from six of the factors outlined above, the three independent factors and factors (3), (8), and (9), and the magnitude of the error in any vertical-strain value will depend on the cumulative effect of the individual contributions from ten of the factors outlined above, all those listed except factor (3).

Each of the individual contributions to the error in vertical stress is random in nature. If the standard error associated with each of the contributions is assumed to be 1 percent of the peak-stress value, an assumption considered to be somewhat conservative, the standard error associated with any value of stress is 2.45 percent of the peak-stress value. (See, for example, Part V of Kissam, 1956.)

The individual contributions to the error in vertical strain which are random in nature stem from the three independent factors and from factors (8) and (9). If the standard error associated with each of these five contributions is assumed to be 1 percent of the peak-strain value, again a conservative assumption, and if the systematic errors are assumed to be negligible, the standard error associated with any value of strain is 2.24 percent of the peak-strain value. The individual contributions to the error in vertical strain which are systematic in nature stem from factors (1), (2), (4), (5), and (11). Those which stem from factors (4), (5), and (11) make the determined values of strain too large;

the one which stems from factor (2) makes the determined values of strain too small, and the one which stems from factor (1) can make the determined values of strain either too small or too large, depending on the type of soil specimen. Consequently, the worst possible situation is one in which the error that stems from factor (2) is negligible, and the errors that stem from the other four factors all make the determined values of strain too large. Although the magnitude of the error which stems from each of the five factors may be considerably larger than 1 percent of the peak-strain value for certain unusual circumstances, the magnitude of the cumulative systematic error probably will not exceed 4 percent of the peak-strain value under ordinary conditions.

If the systematic errors are neglected, the standard error associated with the constrained secant modulus is approximately 3.3 percent of the value of the modulus at peak stress, the exact magnitude depending on the absolute values of the stress and the strain (Kissam, 1956). In other words, if the systematic errors are neglected, the values determined for the constrained secant moduli will be accurate to ±3.3 percent of the value of the modulus at peak stress for approximately 70 percent of the tests conducted. Since it is highly unlikely that the cumulative systematic error will exceed 4 percent of the peak value of the modulus for even 30 percent of the tests conducted, it appears that the values determined for the constrained secant moduli will be accurate to ±7.3 percent of the value of the modulus at peak stress for more than 70 percent of the routine tests conducted.

The other hypothetical situation of interest is one which represents the precision-type tests conducted for fundamental research

applications. It may be assumed that efforts will be expended to minimize the significance of each of the contributions to the experimental error, and that attempts will be made wherever possible to determine the magnitude of the various errors which actually occur.

The most significant errors for the vast majority of the tests of this type will be those which stem from the three independent factors, factors (6), (7), and (10). For tests in which the applied loading pulse is of very short duration (in accordance with Equation 2.1), the errors which stem from factors (3) and (9) are likely to be equally significant. (Recall that factor (3) applies only to the vertical-stress determination.) In any case, the cumulative effect of the nonsignificant errors, either on a vertical-stress value or on a vertical-strain value, will not exceed 1 percent of the peak value of the quantity affected for at least 7 tests out of 10. Therefore, if the standard error associated with each of the significant contributions is assumed to be 1 percent of the peak value of the quantity affected, then the standard error associated with any value of stress is either 2.45 percent or 2.00 percent of the peak-stress value, depending on whether the loading pulse is or is not of very short duration, and the standard error associated with any value of strain is correspondingly either 2.24 percent or 2.00 percent of the peak-strain value.

The standard error associated with a constrained-secant-modulus value for a precision-type research test probably has some value between 2.75 percent and 3.5 percent of the value of the modulus at peak stress in the test of interest. The exact magnitude of the standard error in the range given will depend on whether or not the loading pulse

is of very short duration and on the absolute values of the stress and the strain for which the modulus is determined.

The results of the preliminary testing program provide some indication of the validity of the simplified analyses described above. Compare, for example, the results of two of the tests in the program for which the test conditions were nearly identical, Test Nos. A01A01 and A01R01 (Figs. 119 and 129). The two stress-strain curves obtained have been plotted together for convenience in Fig. 73. If the true stress-strain relationship is assumed to lie halfway between the two curves shown, the magnitude of the error in the constrained-secant modulus at any value of stress does not exceed 2.2 percent of the value of the modulus at peak stress. Compare also the two other pairs of tests conducted under very similar conditions, Test Nos. A01A02 and A01R02 (Fig. 74) and Test Nos. A01P04 and A01R03 (Figs. 128 and 131); the superimposed plots appear in Figs. 74 and 75. For the two tests of relatively long duration, Test Nos. A01A02 and A01R02, the magnitude of the error in modulus does not exceed 1 percent of the peak modulus value; for the two tests of relatively short duration, Test Nos. A01P04 and A01R03, the magnitude of the error in modulus does not exceed 2.5 percent of the peak modulus value. (Note that the three pairs of unloading curves cannot be compared until the position of one or the other in each pair is adjusted so that both unloading curves in the pair emanate from the same peak stress-strain point.)

Although the results of these few tests have no statistical significance, they certainly do not contradict any of the conclusions which can be reached on the basis of the results of the simplified

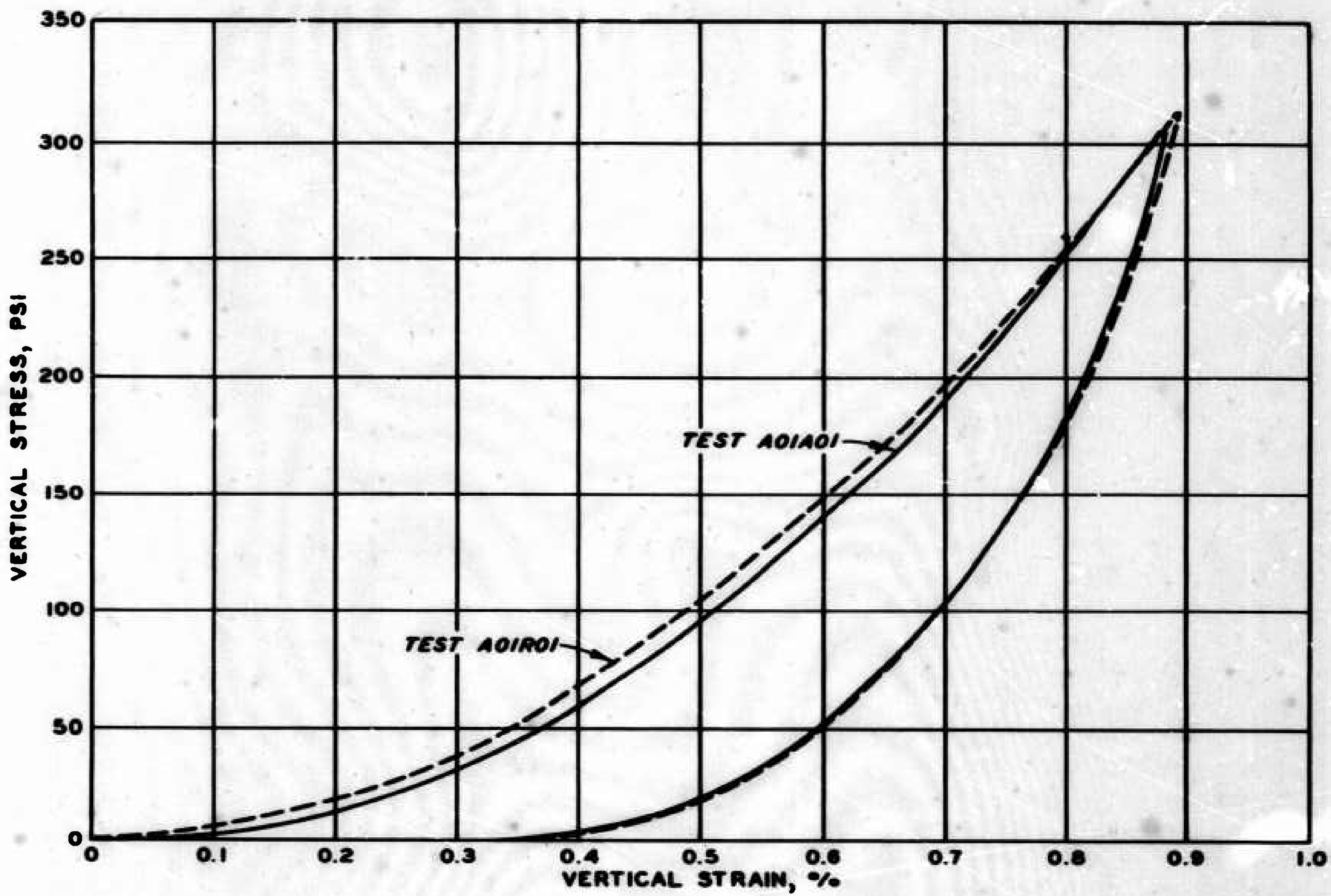


Fig. 73. Comparison of results of Test Nos. A01A01 and A01R01.

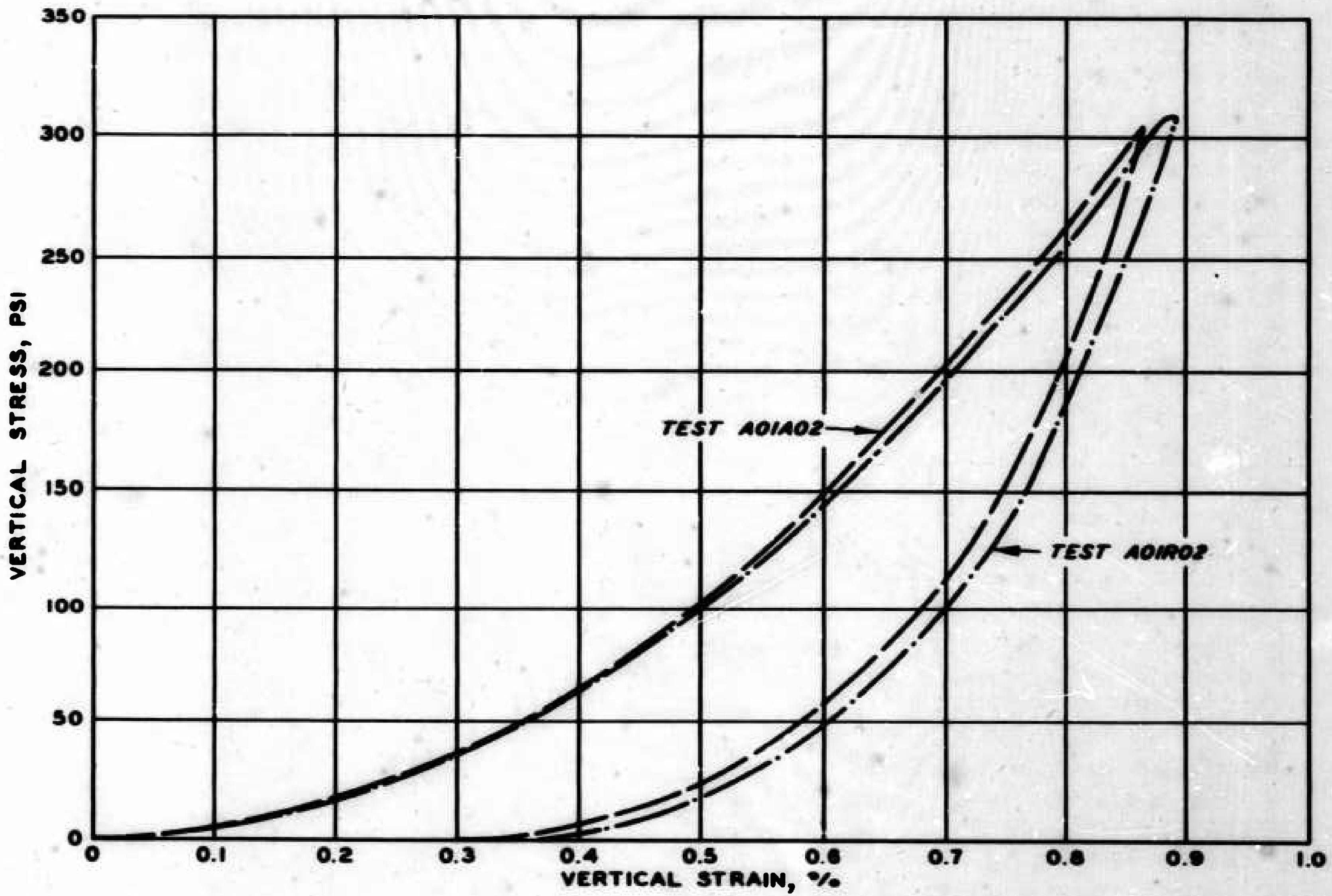


Fig. 74. Comparison of results of Test Nos. A01A02 and A01R02.

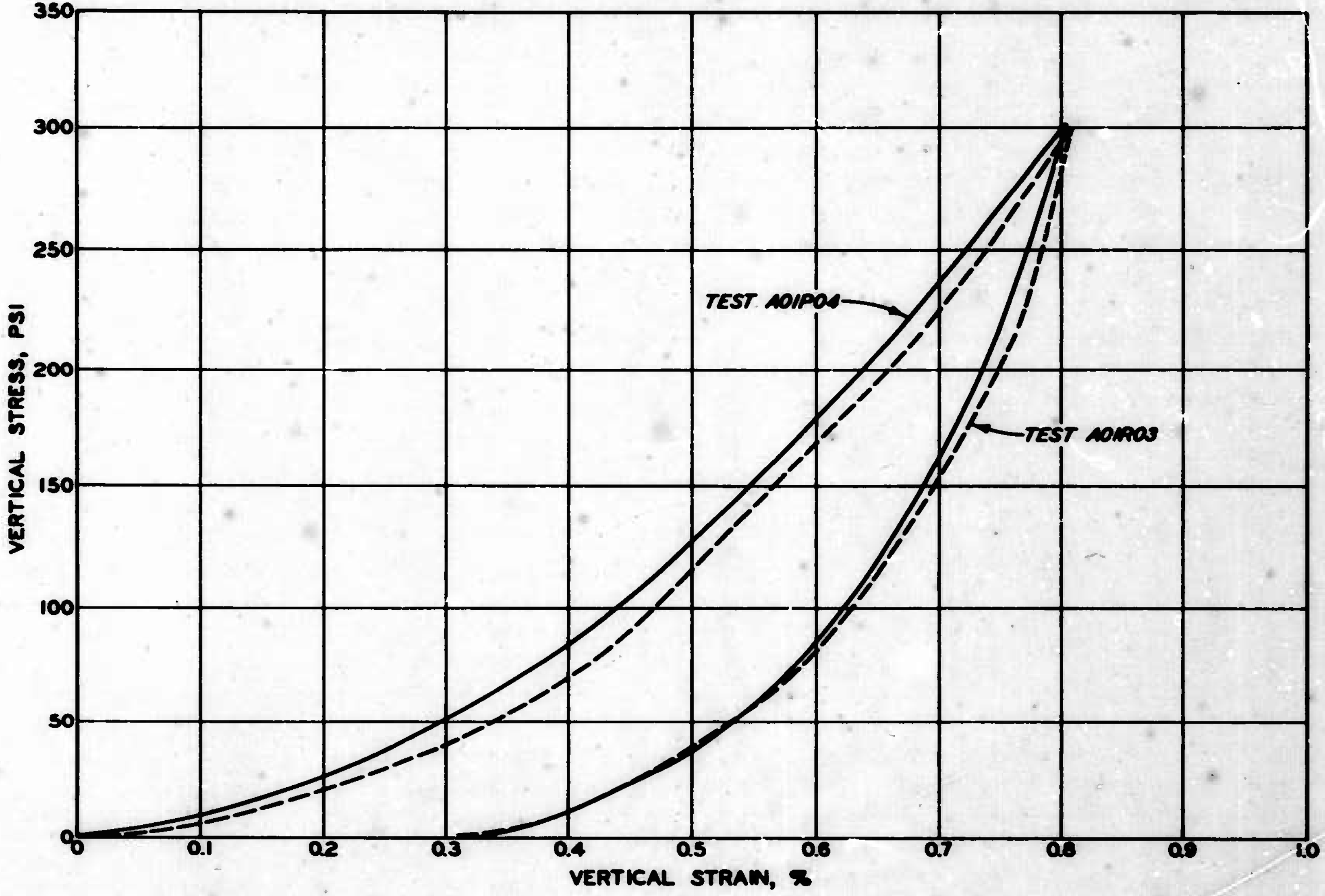


Fig. 75. Comparison of results of Test Nos. A01P04 and A01R03.

analyses described above. Consequently, it may be assumed that the experimental-accuracy capability of the test facility is approximately 7 percent for routine tests and approximately 3 percent for precision-type tests.

4.6.2 Capability Limitations

There are several limitations of varying degrees of importance associated with the general-purpose, one-dimensional compression test facility developed at WES. Most of the limitations have already been discussed in the earlier portions of this chapter. It is appropriate at this time to review those capability limitations which are considered to be of general interest and to consider some methods by which the most important ones can be eliminated or their significance diminished.

Peak Pressure. The only dynamic loading machine currently available for use in conjunction with the WES 10-in.-diam, one-dimensional compression device is the Dynapak. Since the Dynapak loader has an effective peak-load capability of 25 kips, the peak-pressure capability of the test facility is limited to 300 psi, only 33 percent of that for which it was designed.

Four methods are available for extending the peak-pressure capability for short-duration loadings to the originally specified value of 1000 psi.

(1) The development of a high-capacity dynamic loading machine with adequate control capabilities can be undertaken.

(2) A force-multiplier loading technique can be incorporated

into the existing equipment configuration (Fig. 76).

(3) A new device can be built, similar to the existing device, but with a 5-in.-diam piston and soil chamber.

(4) The original auxiliary configuration (Fig. 17, but with the soil container and lower assembly container plate combined into a single member) can be redesigned to accommodate a pneumatic-hydraulic load-application system similar to that employed at MIT or CERF (Section 2.3).

The first method listed appears to be the most promising. Although it will require a greater investment in both funds and time than would any of the other methods listed, the development of a high-capacity loader appears to be the only method for increasing the peak-pressure capability of the WES test facility without adversely affecting the performance and versatility characteristics of the existing facility. It is possible, of course, that another attempt to develop a 100-kip dynamic loading machine will meet with no more success than did the previous attempt. However, the probability of success can be made fairly high simply by incorporating the method of load generation and other key features of the Dynapak loader in the high-capacity machine. (A 50-kip machine similar to the Dynapak has already been developed at the Eric H. Wang Civil Engineering Research Facility of the University of New Mexico.) The previous attempt to develop a high-capacity loader was unsuccessful primarily because the new techniques envisioned by the contractor for load generation and pulse control could not be implemented within the framework of WES' specifications. (It should be noted that a dynamic loader with a capacity of only 78.5 kips would provide the 1000-psi pressure capability required.)

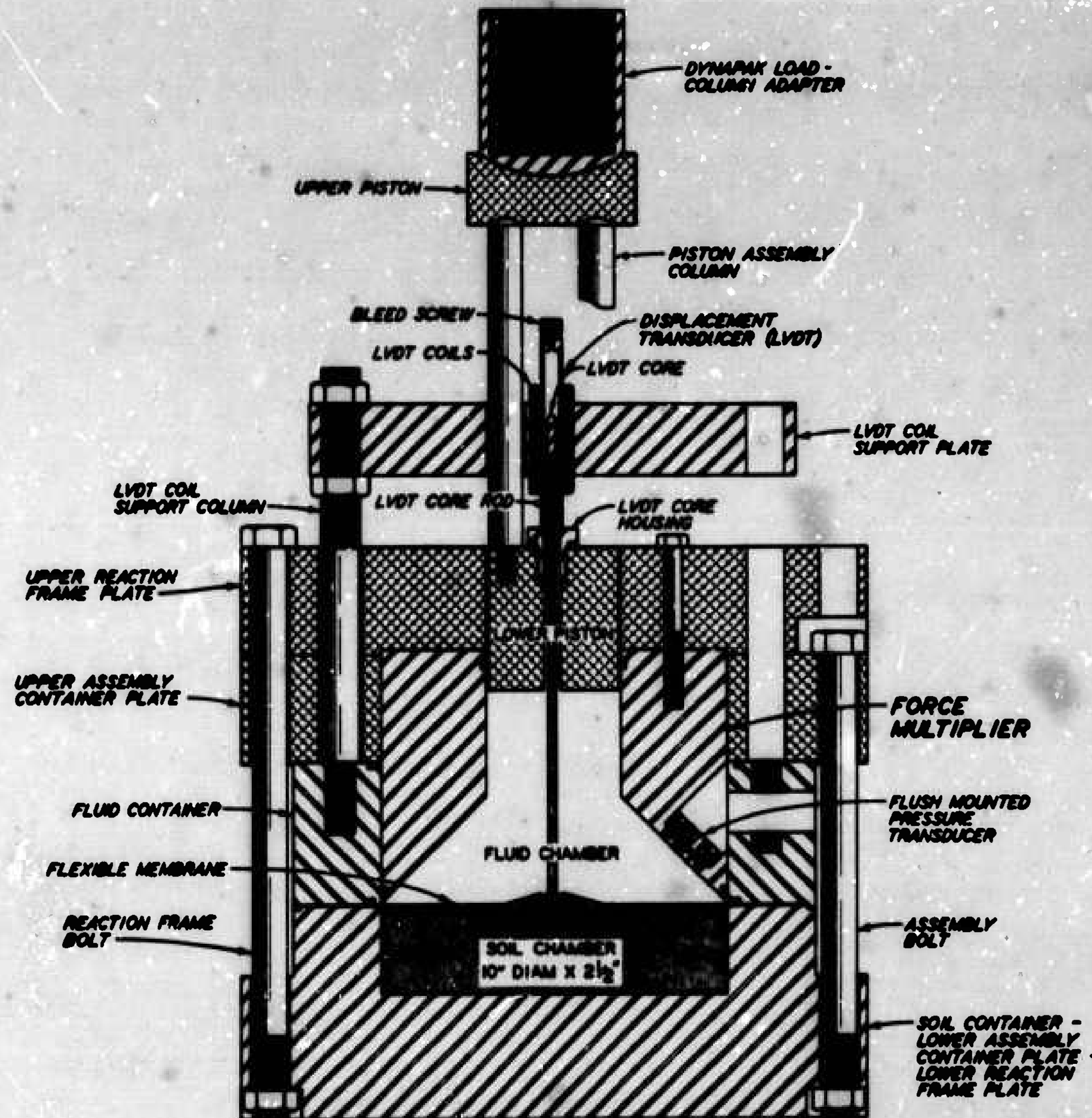


Fig. 76. Drawings depicting use of force multiplier to increase peak pressure capabilities of WES facility.

The last three methods listed should not be dismissed, however. Although it appears likely that implementation of any of these three methods will result in some sacrifice in one or more of the desirable features of the existing facility, there is of course the possibility that the sacrifice will prove to be inconsequential for most conditions of interest. The cost of implementation and evaluation of any of the last three methods listed is so much less than the cost of implementation and evaluation of the first method, that there is a distinct advantage to pursuing one or more of the last three methods before pursuing the first, in spite of the fact that the first appears to be the most promising. An additional advantage afforded by each of the last three methods is the opportunity for conducting short-duration tests to 1000 psi in the very near future, even if only for certain limited conditions.

Of the last three methods listed above, incorporation of a force-multiplier loading technique into the existing equipment configuration appears to be the most promising, and possibly the least costly. The two features of the existing facility which probably will be adversely affected are the uniformity of the applied pressure pulse and the characteristics of the applied pressure pulse (Section 4.3). Clearly, the applied pressure pulse will not be uniformly distributed across the entire surface of the specimen at any given time. However, the degree of nonuniformity almost certainly will be less than that which can be achieved in conjunction with the multiple-reflection testing technique with any load-application system other than the one currently used at WES (see Section 2.3), and it may very well be insignificant for the loading durations of interest. The characteristics of the typical pulse will be

changed when the force-multiplier is incorporated into the existing equipment configuration as a result of the increased flexibility in the load-application system (Section A.6). Although it is clear that the effective natural frequency of the load-application system will be decreased, the effects of the decrease on the characteristics of the applied pressure pulse cannot be predicted readily for the various conditions of interest.

If the peak-pressure capability of the WES test facility were to be extended to 1000 psi by the third method listed, the maximum number of displacement transducers almost certainly would have to be reduced from four to two, and the maximum specimen thickness for any given set of test conditions probably would have to be reduced from that which could be used with a 10-in.-diam specimen. The significance of the limitation on specimen thickness, which could lead to a number of difficulties (see Sections 2.3 and 3.3), depends on the extent of the sidewall-friction effect, and cannot be evaluated at present. Although it appears from the data obtained during the facility-evaluation program that the limitation would be significant for a number of specimens of interest, the data are very limited and inconclusive (see Section 4.5). If the results of the planned sidewall-friction study show that a thickness of 2-1/2 in. or even 2 in. could be used in conjunction with nearly all 5-in.-diam specimens of interest without significantly affecting the accuracy of the data obtained, then extending the peak-pressure capability of the test facility to 1000 psi by building a 5-in.-diam device would be preferable to developing a high-capacity dynamic loading machine. The small sacrifice in the capabilities of the test facility would be more than compensated for by the savings in time and money.

The fourth method listed is the least promising in that it results in all the limitations associated with fluid-loading test facilities (see Section 2.3). Nevertheless, if it can be shown that the incorporation of the force-multiplier would cause severe oscillations in the applied-pressure pulse, and if it can be shown that a 5-in.-diam device would be unsatisfactory as a result of sidewall-friction effects, then the fluid-loading technique may be worthy of consideration. It has already been shown that the difficulties which result from the conflicting requirements of the load-application system and the measurement system (see Section 2.3) can be eliminated by using a core housing. It may be that the consequences of nonuniform loading will not be significant for most of the conditions of interest. If this were the case, and if a fairly simple and inexpensive concept for controlling the characteristics of the applied loading pulse could be formulated, then extending the peak-pressure capability of the test facility to 1000 psi by using a fluid-loading technique would be preferable to developing a high-capacity dynamic loading machine.

It should be noted that, although there were no clearly established program requirements for applied loadings much in excess of 1000 psi at WES at the time the design of the one-dimensional compression test facility was undertaken, such requirements are being established at the present time (principally in response to the ever-increasing demand for reliable soil-property data needed to support the development of rational, analytical computer codes which can be used to determine the free-field response in the environment of a nuclear explosion). Extension of the peak-pressure capability of the WES test facility to a value significantly

greater than 1000 psi (say to 10,000 psi), without adversely affecting the performance and versatility characteristics of the existing test facility, probably will require the development of a well-controlled, very high-capacity, ram-type, dynamic loading machine. The development of such a machine now appears to be feasible. A 4-ft-diam, overpressure-type, dynamic loading machine with good control features is currently being developed for WES, and another such machine (based on a completely different design concept) is already in operation at the University of Illinois. If either of the two proven concepts for applying a controlled, impulse-type pressure pulse uniformly to a large surface were incorporated in a ram-type, dynamic loading machine, an order-of-magnitude increase in capacity over currently available ram-type loaders could be achieved.

Pressure-Pulse Characteristics. The characteristics of the Dynapak-generated pressure pulse are controlled by four settings--one for the rise time, one for the dwell time, one for the decay time, and one for the magnitude of the peak load. In spite of this control capability, the general shapes of all pulses are very similar. A typical pulse is shown in Fig. 39, and its characteristics are described in Section 4.3.

One of the features of the typical Dynapak-generated pressure pulse not considered to be particularly desirable for most applications is the fixed, nearly linear, pressure-time relationship during unloading. Nevertheless, the fixed shape of the unloading pulse is not considered to be a significant limitation, even for tests conducted for research applications. The shape of any desired unloading pulse can be satisfactorily simulated for most applications by a nearly linear pulse with the same

impulse. Consider, for example, the surface air-blast loading from a 100-MT nuclear surface burst at the 300-psi overpressure level (Fig. 77). It appears reasonable to assume that the response of a specimen to Pressure Pulse A (Fig. 77) will not differ significantly from its response to the actual pressure pulse. The assumption can always be verified by subjecting duplicate specimens to Pressure Pulses B and C (Fig. 77), thereby bracketing the impulse of the actual pulse and (presumably) the response of the specimen as well.

Another feature of the typical Dynapak-generated pressure pulse thought to be generally undesirable is the presence of oscillations in the rise portion of the pulse. The fact that the rise portion of the pulse is not monotonic, as desired, does not appear to be important, however, since the quality of the data actually obtained does not appear to be adversely affected by the small, cyclic perturbations caused by the low-amplitude oscillations. Consider, for example, the actual stress-strain data points from Test No. A01P03, the test for which the oscillations were particularly severe (Fig. 127). The data points are presented in Fig. 78, where the actual stress-strain behavior during the test is indicated. Clearly, the smooth stress-strain relationship shown in Fig. 127 does not differ significantly from the relationship which would have been determined had there been no oscillations in the pressure pulse.

The oscillations in the rise portion of the typical pressure pulse result not only in cyclic perturbations of loading and unloading, but also in time delays in the rise portion of the pressure pulse (see Section 4.3). Although the loading and unloading effect probably is not important, the time delays in the rise portion of the pressure pulse

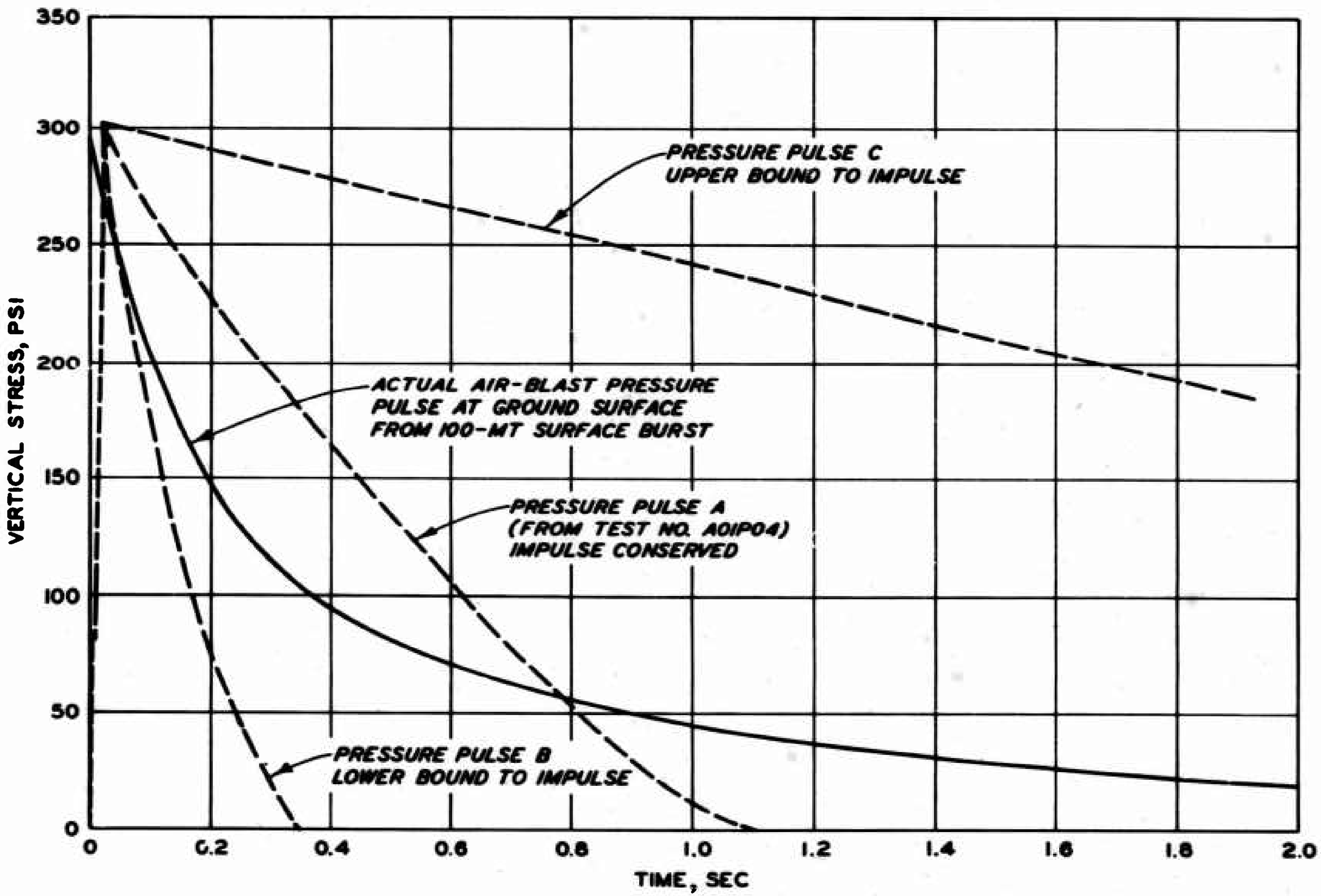


Fig. 77. Simulating and bracketing a pressure pulse of interest with the Dynapak loader.

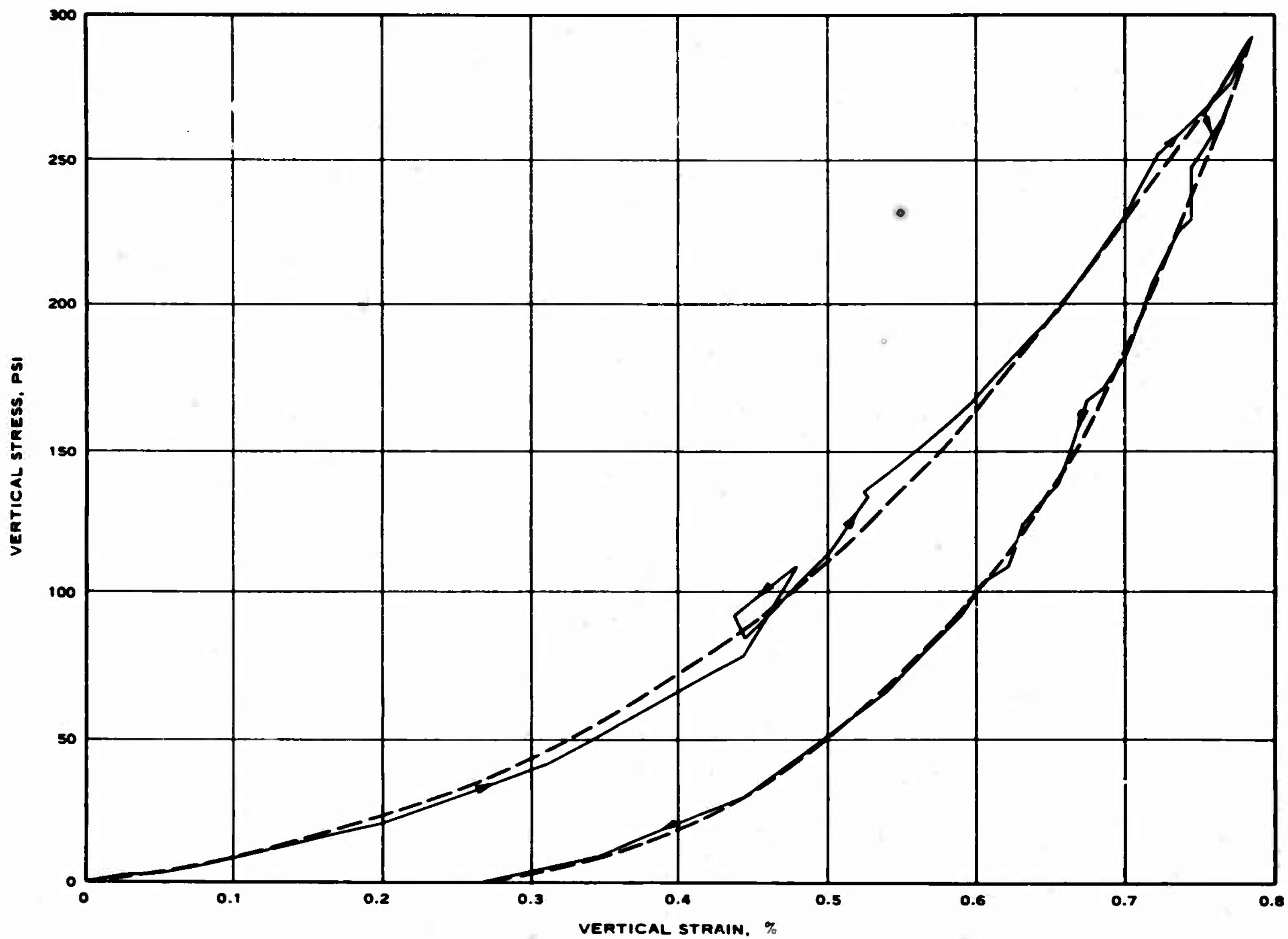


Fig. 78. Effect of pressure-pulse oscillations on data obtained.

undoubtedly are, particularly for tests conducted on materials whose response characteristics are highly time sensitive. The fastest rise time which can be used for a given set of conditions is, after all, already limited by the very nature of the multiple-reflection testing technique (Section 2.2). The technique-related limitation, as defined by Equation 2.1, is not considered to be significant in itself for most conditions of interest (see Section 2.2); however, the restriction imposed by the time delays which result from the oscillations in the rise portion of the pressure pulse, when added to the technique-related limitation, clearly represents an important limitation on the capability of the test facility.

The oscillations which appear in the rise portion of the typical Dynapak-generated pressure pulse represent the free-vibration component of the transient response of the load-application system (see Section A.6), and there is little that can be done to eliminate them in the existing test configuration. However, it may be possible to eliminate the oscillations in the test configuration used to extend the peak-pressure capability of the facility to 1000 psi. If the increased capability is achieved by developing a high-capacity loader, some consideration should be given to the possibility of incorporating a variable-mass load column in the loader, so that some control can be exercised over the natural-frequency characteristics of the load-application system. If the increased capability is achieved by any of the other methods listed above, there probably would be little, if anything, that could be done to eliminate any oscillations which occur; on the other hand, there may not be any oscillations present when the new configuration is used.

Initial Pressure. The combined weight of the Dynapak load

column, the load-column adapter, and the piston assembly is approximately 230 lb. (The weight of the pressure fluid is negligible.) Although this corresponds to an initial pressure of slightly less than 3 psi applied to the specimen surface, laboratory measurements have shown that the initial pressure is actually more nearly 1.25 psi (the difference no doubt resulting from friction at the locations of the various O-rings in the load-application system). The Dynapak load column (and the attached adapter) can be supported inside the loading machine prior to the application of a pressure pulse, if so desired. When this is done, only the weight of the piston assembly (approximately 75 lb) acts on the pressure fluid, and the initial pressure applied to the specimen surface is approximately 0.6 psi (according to laboratory measurements). Since there is no method presently available for supporting the piston assembly from above, the minimum value of initial pressure for any test is approximately 0.6 psi.

The effect of an initial pressure of 0.6 psi can probably be neglected for all conditions of interest, since the WES one-dimensional compression device was designed primarily for applied pressure pulses in the 100- to 1000-psi range (Section 3.1). If it should become necessary to conduct a test with an initial pressure less than 0.6 psi and a pressure increment in the 1- to 100-psi range, the assembly technique currently in use (Section 4.2) should be modified slightly to permit the LVDT coil support plate to be placed and locked in position in the assembly before the fluid chamber is filled with the pressure fluid. In this way, the specimen deformations resulting from the application of the initial pressure can be measured. (It is recognized that the response of any given soil specimen to the two-stage load-application process may

not be the same as its response to the total pressure applied as a single increment, particularly for the case of a short-duration pressure increment; nevertheless, it is anticipated that the difference in response will be insignificant in most cases.)

There is certainly a very good possibility that an initial pressure of less than 0.6 psi will never be required. When a specimen is taken from a mass of soil in the field, the weight of the soil above (overburden) is removed. Although the change in the states of stress and strain--and, hence, in the response characteristics--of the material is not known, the best method available for returning the specimen to its presampling condition (or, to a condition close to it) is to apply an initial pressure to the specimen equal to the weight of the overburden. Since an initial pressure of 0.6 psi is approximately equivalent to the weight of 1 ft of overburden material, and since the behavior of the top foot of material in the field is rarely (if ever) of interest, the 0.6-psi limitation is clearly unimportant. (The top foot of soil in the field at any location of interest is far more often removed than not, and is replaced by a compacted fill which is insensitive to an initial pressure of 0.6 psi). Because initial pressures less than 0.6 psi are not of interest for practical applications, it is reasonable to assume that there will be no important research requirements for initial pressures less than that value.

Specimen Seating. A specimen which is simultaneously prepared and placed inside the soil chamber (by one of the methods shown in Fig. 19, for example) is satisfactorily seated on its supporting surface as a direct result of the method of placement used. A tube-

(or ring-) contained specimen, on the other hand, cannot be seated satisfactorily on its supporting surface simply by placing the tube on the base of the soil chamber, since it is highly unlikely that the combined tube-specimen surface will be mechanically coupled to the base of the soil chamber at many points on the interface. Even when the bottom surface of a rigid-specimen-simulating steel plate was carefully mated to the base of the soil chamber by lapping, a seating displacement of approximately 1.5 mils occurred at the interface (see results of Test No. A01A05, Fig. 124). Since there is no convenient method available for mating the bottom surface of a soil specimen and the tube in which it is contained to the base of the soil chamber, seating displacements greater than 1.5 mils can be anticipated. It is important to recognize that a seating displacement at the specimen-soil chamber interface directly beneath the disc for LVDT No. 0 results in an error in the specimen-deformation measurement equal to the magnitude of the seating displacement. (Seating at the interface at a location removed from the center of the device also results in an error in the measured specimen deformation, in that it permits the portion of the specimen directly beneath the disc for LVDT No. 0 to strain laterally under the applied load.) Consequently, unless a method can be found which (1) minimizes the effect of seating displacements on the specimen-deformation measurement, or (2) provides a satisfactory seat in the soil chamber for tube- (or ring-) contained specimens, the types of specimens for which the experimental-accuracy capability of the facility as a whole (as outlined in the previous subsection) is valid will be somewhat limited.

The two most obvious methods for solving the specimen-seating

problem--(1) applying a small seating load prior to the test, and (2) correcting the data obtained for the seating displacement which occurred--do not have general application for the tube-contained, one-dimensional compression soil specimens of interest. The application of a small seating load, which can generally be justified as a real or hypothetical (depending on the type of specimen) overburden-simulating initial pressure, may be sufficient to seat some specimens against the base of the soil chamber, although unjustifiably high seating loads will probably be required for others. In either case, however, since there is unlikely to be much information available concerning the details of the constrained constitutive characteristics of the particular materials tested, it will probably not be possible to make an accurate estimate of the magnitude of the seating loads required; nor is it likely to be possible to determine whether the actual overburden-simulating initial pressures are sufficient to seat the specimens satisfactorily. For the same reason, it will probably not be possible to correct the data obtained for the seating displacements which occur, since it is not likely to be possible to recognize seating displacements in the observed specimen response.

Two methods appear to be feasible for solving the seating problem for the general tube-contained one-dimensional compression specimen, although both require some study before they can be satisfactorily implemented. One method involves the use of fairly long specimens, for which the seating displacements would be small in comparison with the specimen deformations. The most important difficulty to be overcome in connection with this method is the sidewall-friction effect.

Although a great deal of effort has already been expended in this area, in connection with field-simulating, laboratory wave-propagation devices (Baker, 1967; Zaccor, Mason, and Walter, 1964; Hampton and Wetzel, 1966; Seaman, 1966; Stoll and Ebeido, 1964), it is still not clear whether any of the devices that have been built satisfactorily limit sidewall friction and also lateral strain. The sidewall-friction-reduction technique which appears to be most promising and most readily adaptable for use in conjunction with a general-purpose one-dimensional compression device is the stacked-ring or stacked-tube technique, show schematically in Fig. 79.

Before the stacked-tube-type one-dimensional compression device can be used with confidence, however, several details associated with its use will have to be carefully investigated. Most important of the details is clearly the selection of a suitable filler material, one which is sufficiently flexible (even when confined) to prevent vertical load transfer to the specimen boundary, sufficiently plastic (perhaps when heated) to be injected between the tube sections, and sufficiently rigid to prevent lateral squeezing of the specimen. The effect of machining grooves in the tube, which generates both heat and vibrations, will have to be determined, and the tendency for buckling will have to be investigated. In fact, since the stacked-tube device is in no way similar to the 10-in.-diam one-dimensional compression device described herein, all aspects of the stacked-tube device will have to be evaluated to determine if the experimental-accuracy capability associated with it exceeds that of the existing device for tube-contained specimens.

The alternative to a new stacked-tube-type device involves

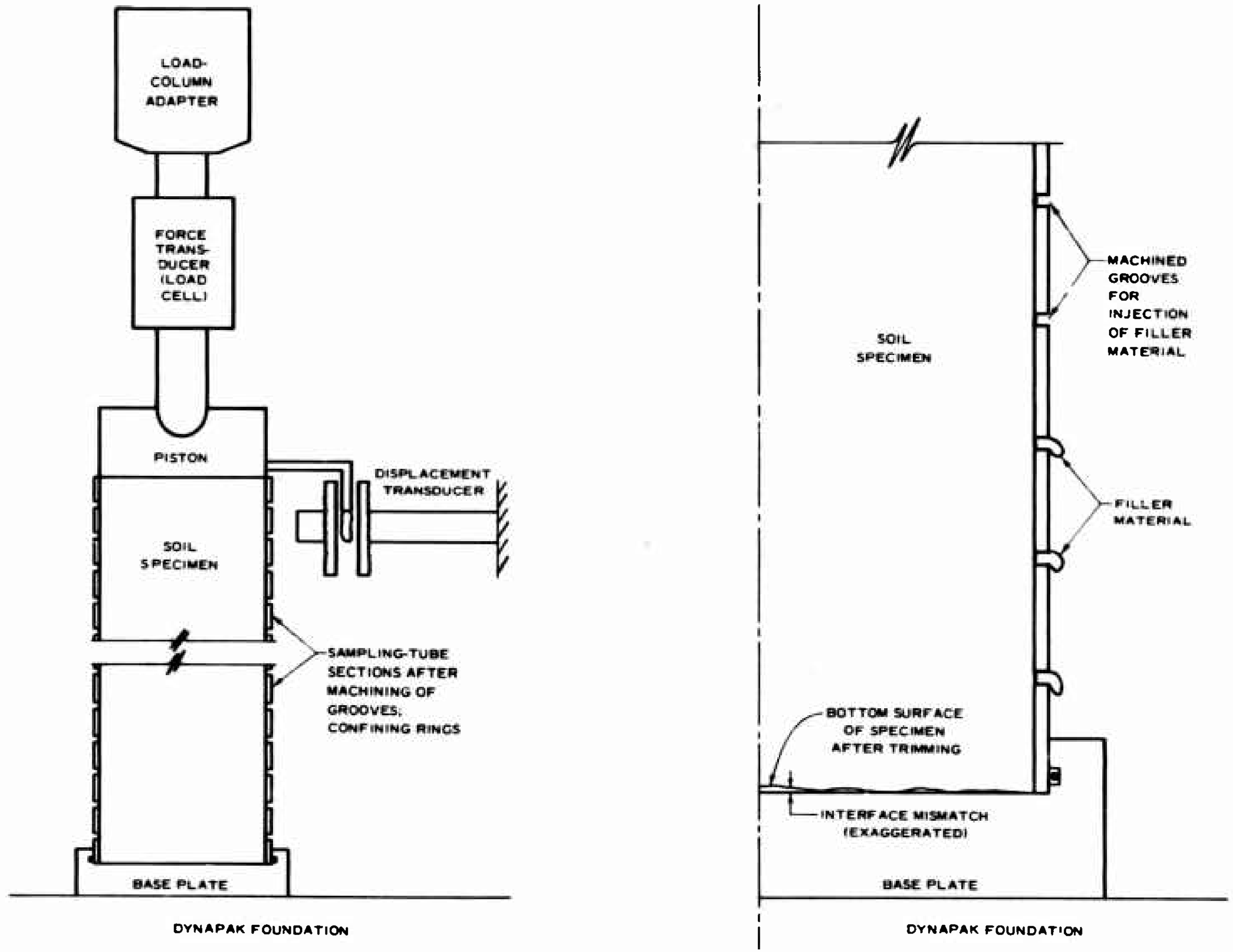
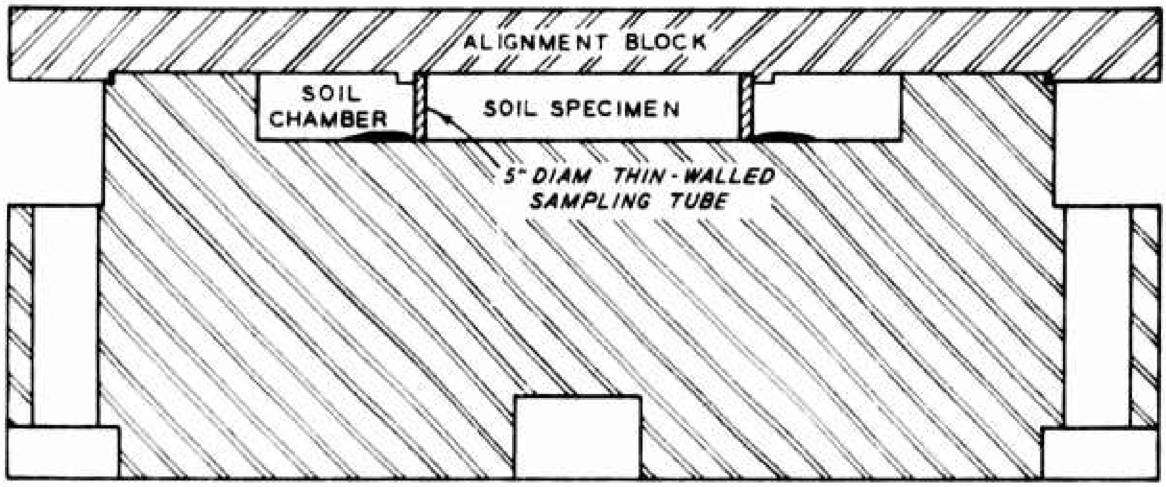


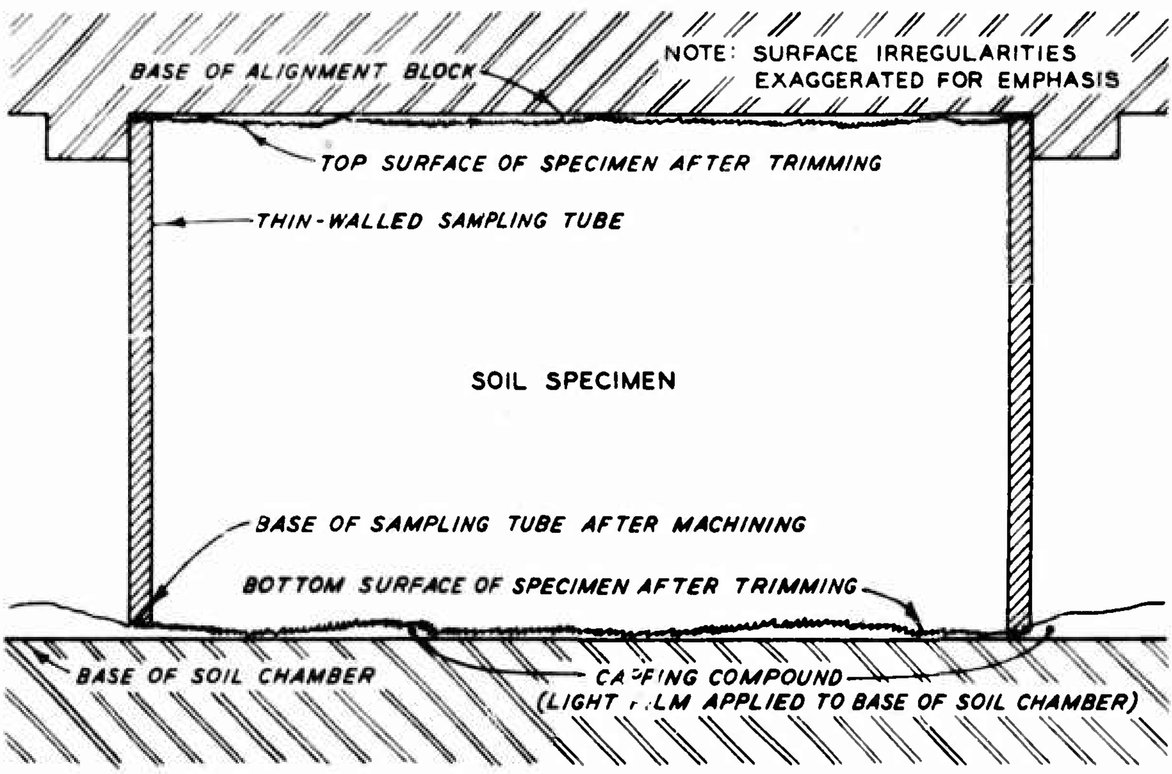
Fig. 79. Schematic drawing depicting use of stacked-tube device for tube-contained specimens.

the use of a capping compound at the specimen-soil chamber interface, as illustrated in Fig. 80, to solve the seating problem in the existing device for tube-contained specimens. (The capping compound would also prevent leakage of pore fluid from the specimen.) Before the use of this method can be implemented, however, a suitable capping-compound material will have to be found. The material should be sufficiently fine-grained to permit its use in thicknesses of approximately 1 mil, sufficiently plastic before setting to flow between the tube and the base of the soil chamber when the tube is slowly placed in position, sufficiently rigid after setting to deform less than 0.05 mil at 1000 psi when fully constrained (for which a constrained modulus of only 20,000 psi is required), and sufficiently active chemically to be readily soluble in some solution which does not attack stainless steel. The rigidity requirement can be reduced by an order of magnitude, or more, if the constrained constitutive relation for the material is found to be repeatable to 10 percent or better.

The capping-compound method appears to have many advantages over the stacked-tube, long-specimen method, and is clearly the one which should be investigated first, if possible. Not only are there less apparent problems to be investigated with the capping-compound method, but the rewards of success promise to be greater also. If a suitable capping-compound material can be found, the experimental-accuracy capability of the facility already demonstrated for 10-in.-diam prepared specimens will be extended to include large-diameter tube-contained specimens, without any sacrifice in the advantages of the existing facility, without any modifications to the existing facility,



a. OVERALL VIEW



b. DETAIL OF SPECIMEN

Fig. 80. Schematic drawing depicting use of capping compound for tube-contained specimens.

and without the need for an additional facility-evaluation program. Even if the stacked-tube device proved to be successful, it would have at least three disadvantages in comparison with the existing device: (1) field samples would be difficult and expensive to obtain (since long good-quality specimens will be needed) and to prepare, (2) the minimum rise time which could be used, according to Equation 2.1, would be approximately an order or magnitude greater than that generally required, and (3) the lateral-strain resistance capability of the thin-walled tubes would probably not be satisfactory for many specimens of interest. In addition, the design, fabrication, and evaluation of a completely new device would have to be undertaken.

CHAPTER 5

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Summary

A general-purpose test facility for determining the one-dimensional compression characteristics of soils subjected to impulse-type loads has been developed in order to help satisfy the ever-increasing demand for reliable soil-property data required in support of a wide variety of nuclear-weapons-effects-related problems. The design, fabrication, installation, and evaluation of the various elements which together comprise the test facility were accomplished at the U. S. Army Engineer Waterways Experiment Station (WES), where much of the Defense Atomic Support Agency-sponsored, nuclear-weapons-effects research program is conducted.

A drawing of the basic assembly for the newly developed, WES, general-purpose, one-dimensional compression test facility is shown in Fig. 81, and a photograph of the assembly is shown in Fig. 82. The short-duration, single-impulse loads of interest are generated inside a dynamic loading machine and are applied to the piston assembly of the device by the load column of the dynamic loading machine. A schematic drawing of the Dynapak loader, the dynamic loading machine currently being used, is shown in Fig. 83, and a photograph of the assembled device in position for a test is shown in Fig. 84. The two key measurements, from which the vertical stress and strain in the specimen are determined, are made by a flush-mounted, diaphragm-type, strain-gage pressure transducer and an LVDT-type displacement transducer (Fig. 81); provisions have also been made for a number of support-type measurements, which can be made as desired. The

measurement system used is shown schematically in Fig 85. The various electromechanical transducers which are used to obtain the measurements are shown in Fig. 86, and the instrumentation room where the measurements are recorded (and where the electronic control apparatus for the Dynapak loader is located) is shown in Fig. 87.

The multiple-reflection testing technique used is basically a static-type testing technique in that no significant inertial stresses are permitted to develop within the specimen during the test. The time required for propagation of a stress pulse through the relatively thin specimen used is so small relative to the rise and decay times of the applied load that there is little or no opportunity for the development of vertical-stress differences in the specimen; any which do occur are very soon eliminated as a result of internal reflections. Consequently, although the time characteristics of the applied loading pulse may be selected to simulate those of the air blast and ground shock from a nuclear explosion, the specimen is uniformly loaded throughout the test. The multiple-reflection testing technique, then, affords the opportunity for determining the response characteristics of a soil specimen under the conditions of interest without the need either for a long specimen or for buried instrumentation, both of which are generally undesirable.

The various elements which comprise the general equipment assembly or device include a soil container, a fluid container, an upper assembly container plate, a piston assembly, a load-column adapter, a support structure for the zero-reference portions of the four displacement transducers (LVDT's) which can be used, and a set of LVDT core housings (Fig. 81). The soil container serves not only to contain the soil specimen (i.e., to

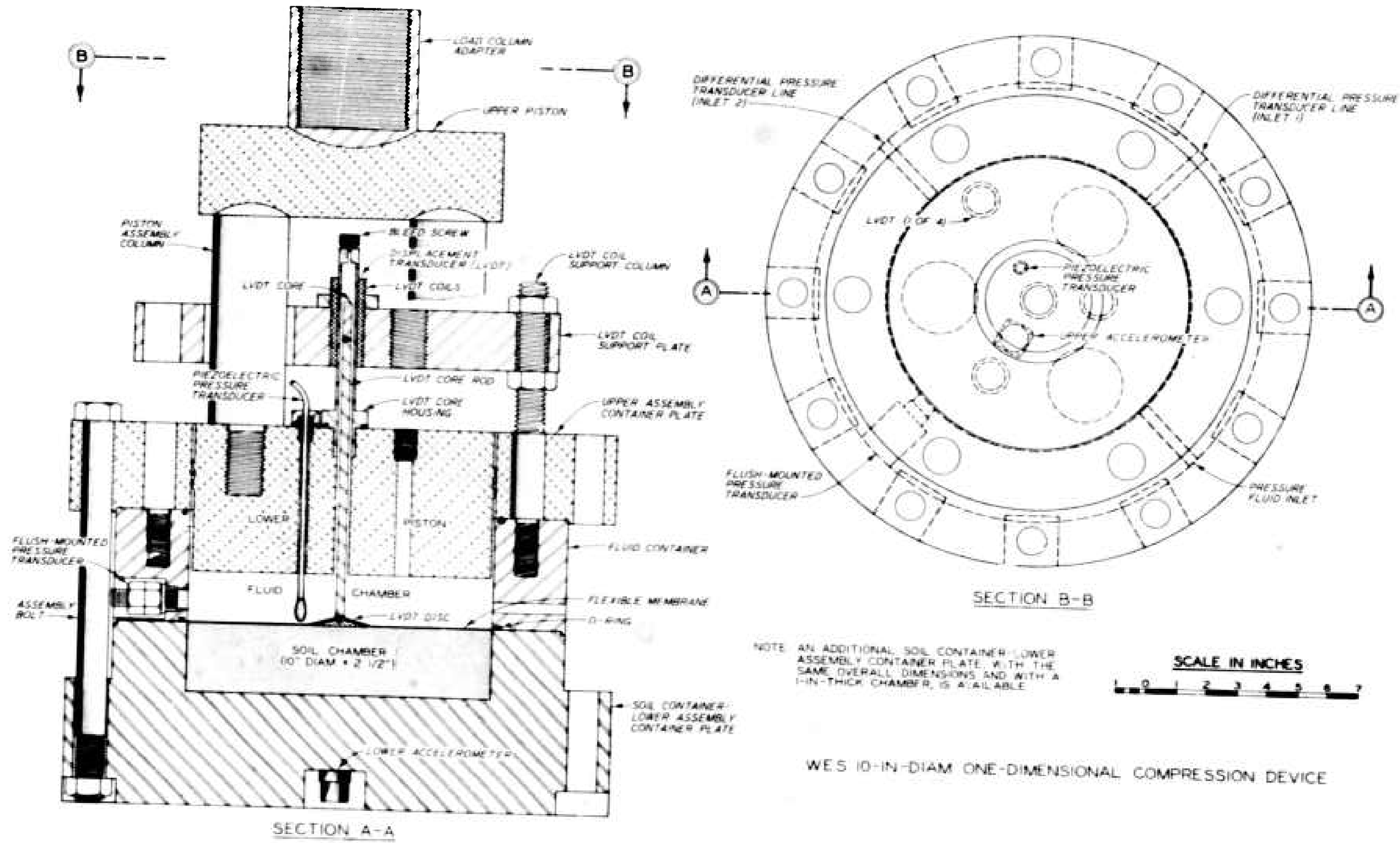


Fig. 81. Drawing of basic assembly.

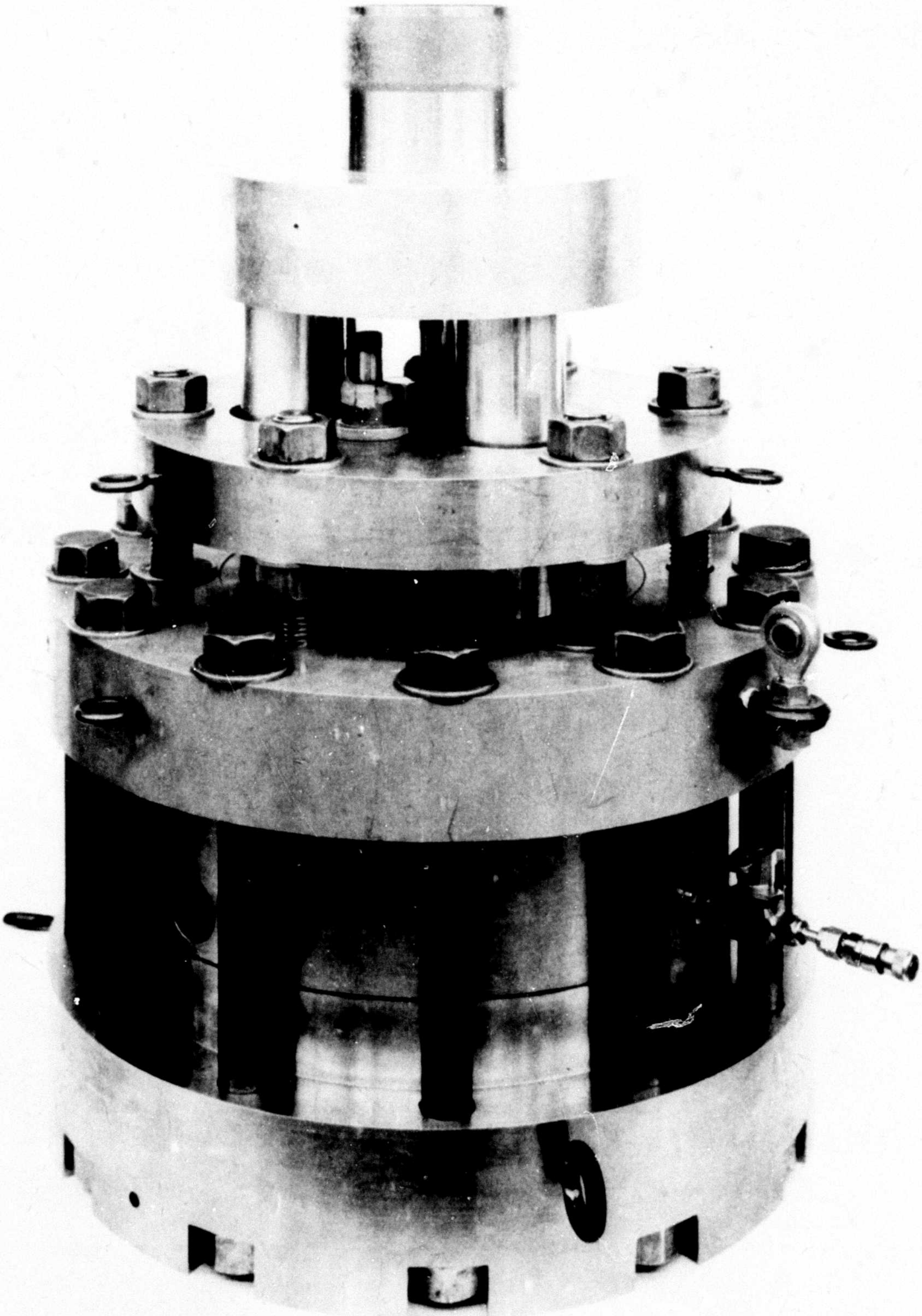


Fig. 82. Photograph of basic assembly.

prevent the escape of both soil particles and pore fluid) under load, but also to provide the specimen with a lateral boundary which is capable of maintaining the condition of no lateral strain that characterizes the one-dimensional compression test. The purpose of the fluid container is simply to contain the loading fluid. Three of the four equally spaced holes through its wall are for hydraulic purposes and are terminated by sealed fittings and valves; the fourth hole contains the flush-mounted pressure transducer. The function of the upper assembly container plate (which could have been made integral with the fluid container) is to provide a convenient means for bolting the fluid container to the soil container, thereby compressing the O-ring at their interface and sealing the pressure chamber without the somewhat undesirable condition of having large-diameter holes in the soil-container wall. (The lower assembly container plate was made integral with the soil container in order to provide a rigid support for the soil specimen and thereby reduce equipment compressibility to a minimum.) The piston assembly--which includes the upper piston, the lower piston, and the three assembly columns--and the load-column adapter provide the transition configuration required to transfer load from the flat-based load column of the dynamic loading machine (Fig. 83) to the fluid-filled chamber above the specimen. The LVDT coil support plate and columns carry the support of the zero-reference portions of the displacement transducers (i.e., the LVDT coils) to the fluid container, which is rigidly connected to the soil container by the assembly bolts. Hence, even though the LVDT coils cannot be placed conveniently in their ideal locations directly beneath the soil specimen inside the base of the soil container, they are effectively connected to these ideal locations. The function of the LVDT

core housings is to provide a sealing mechanism for the sensing portions of the displacement transducers without in any way restricting their freedom of motion.

The single-piece soil container shown, although basically very simple, permits a great deal of versatility in the nature and size of specimen which can be accommodated; hence, it is very well suited to general-purpose applications. A prepared specimen can be placed directly into the soil chamber of the device by any of the conventional placement techniques, or it can be placed either into an insert ring which fits exactly into the soil chamber or into a smaller diameter ring which is placed in the center of the chamber and then surrounded by a constraining medium (either soil or a rigid fluid with a membrane leakage barrier). An undisturbed specimen in a sampling tube similarly can be placed in the center of the soil chamber and surrounded by a constraining medium after the ends of both the specimen and the tube have been properly prepared to fit. A sampled block specimen, once trimmed into a ring, is the same as the ring-contained prepared specimen. Although the tube- (or ring-) contained specimen does not encounter a solid boundary, as does the specimen prepared directly inside the soil chamber, the tendency of soil particles and pore fluid to be squeezed out under the confining tube is resisted by the same pressure that causes it, since the pressure fluid above the tube pushes and seals the tube against the base of the soil chamber; additional resistance is provided by the pressurized constraining medium. Consequently, all types of specimens are adequately contained under load. The sidewall-friction problem typically associated with a solid boundary is relatively insignificant for the WES device, because the displacement transducer which measures the response of

the soil specimen is located in the central portion of the large-diameter (relative to thickness) specimen, far removed from the sidewall.

The dynamic loading machine used to provide the short-duration, single-impulse loading pulses of interest operates on the cold-gas-expansion principle (Fig. 83). For the loading portion of the pulse, a large volume of pressurized gas is collected behind a rapid-acting valve, on the other side of which is a large collar attached to the load column; when the valve is opened, the high-pressure gas expands into the small volume (relative to the initial volume of pressurized gas) above the load-column collar, and the load column is accelerated against the piston assembly of the device. For the unloading portion of the pulse, a special rapid-acting valve is used to accelerate the rate of decay beyond that which can be achieved by simple release of the pressurized gas. All the characteristics of the loading pulse can be controlled quite accurately by selecting the proper settings for a series of valves and timers prior to the test. Consequently, it is possible to simulate and certainly bracket nearly all short-duration loads of interest within the peak-load capability of the Dynapak loader.

The load from the Dynapak load column is transmitted to the soil specimen through a piston assembly and confined fluid (Fig. 81). The piston assembly makes it possible to transfer the load from the single load column to the piston above the pressure fluid without adversely affecting the operation of the displacement transducer at the center of the specimen (or that of any of the other displacement transducers, for that matter). The pressure fluid between the piston and the upper specimen surface serves a number of purposes. It applies a uniform pressure pulse to the entire specimen surface, as required for one-dimensional compression, regardless of

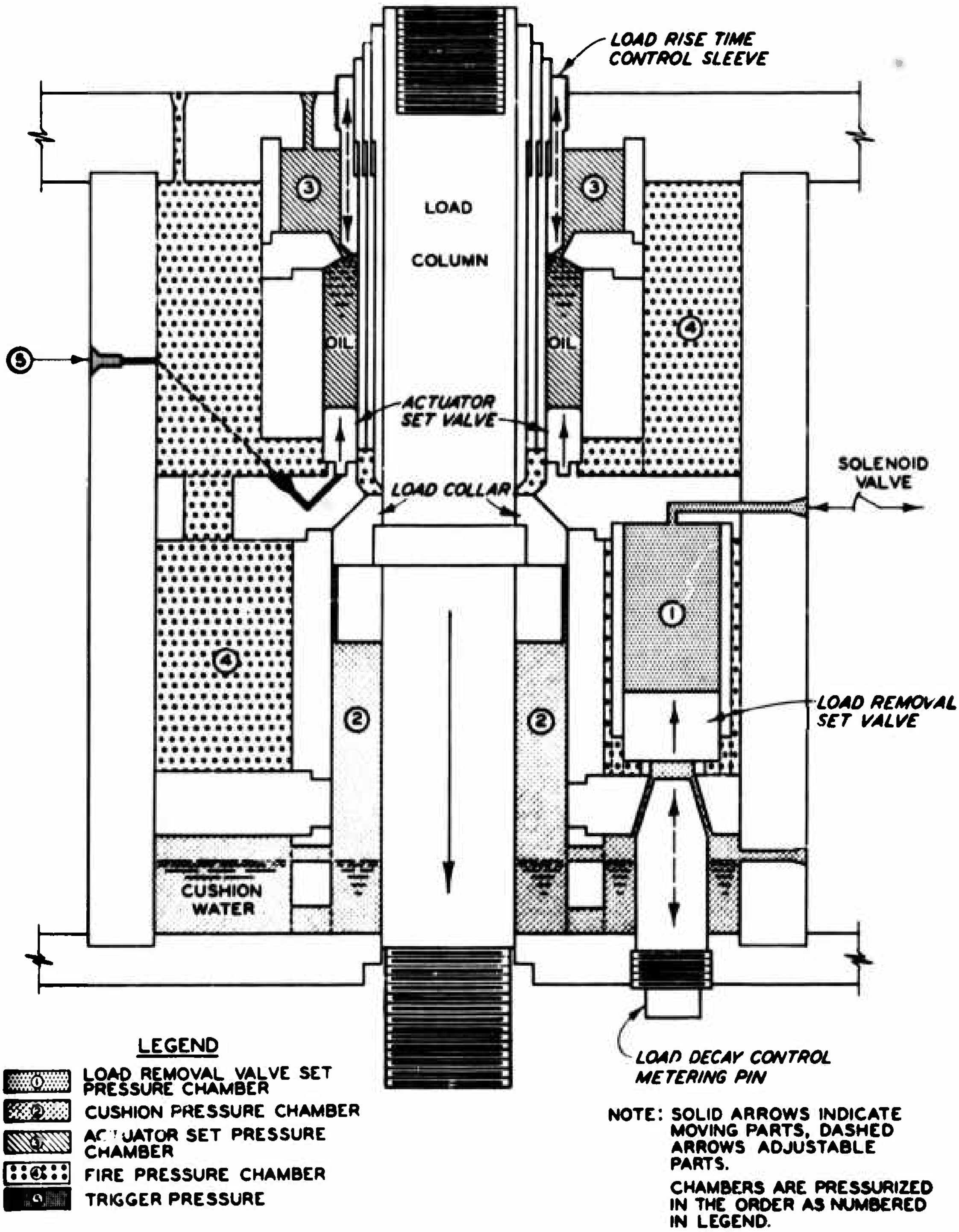


Fig. 83. Schematic drawing of dynamic loading machine (from Cunny and Sloan, 1961).

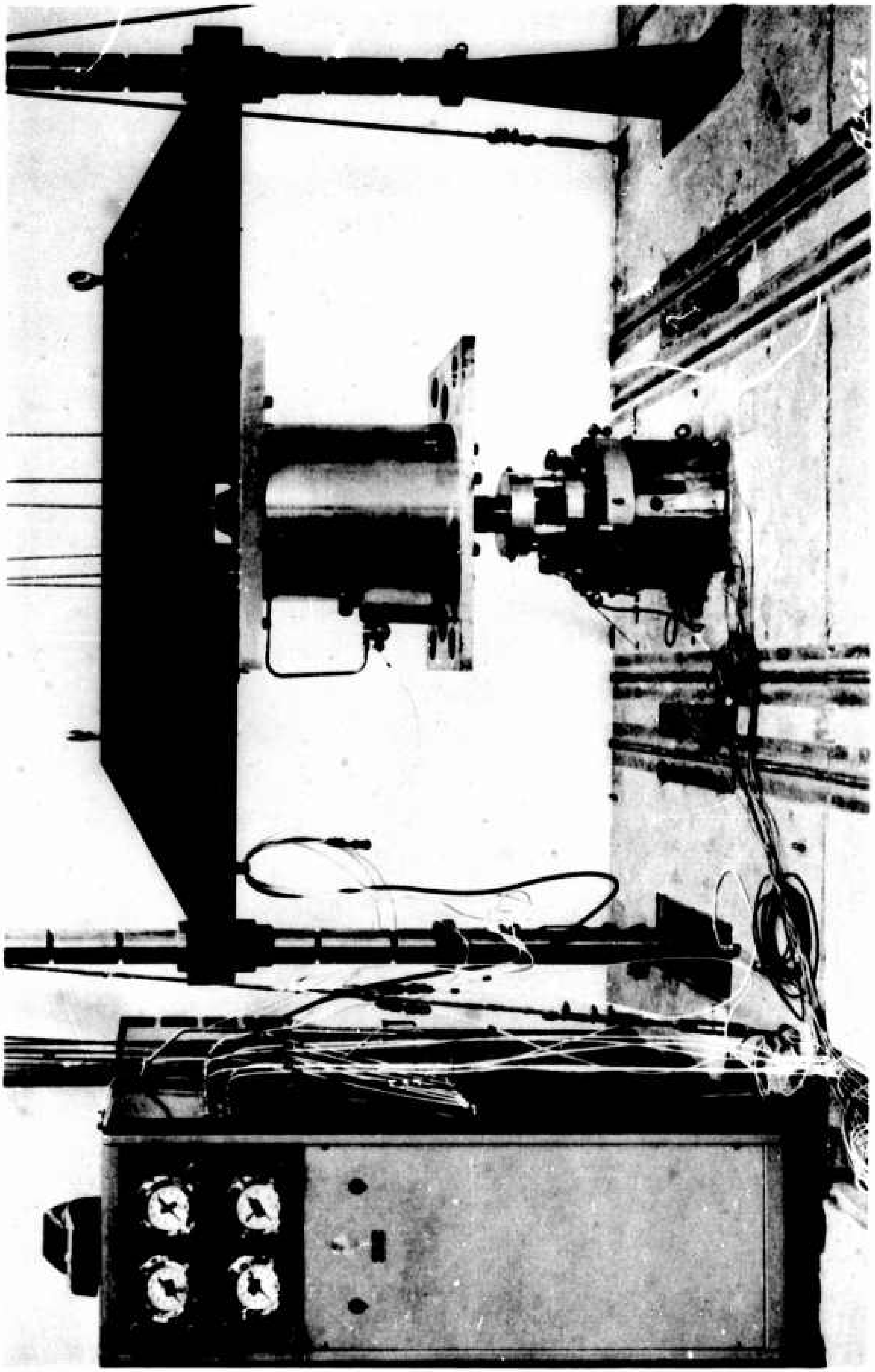


Fig. 84. Assembled device in position for test.

any differences in specimen stiffness which may result from sidewall friction or other sources. It also acts as part of the specimen-containment system and (together with the flexible membrane between it and the specimen) prevents the escape of soil particles and pore fluid from the upper specimen surface under load. The pressure fluid apparently also serves as a mechanism for damping in the otherwise rigid load-application system (particularly for very stiff specimens), and thereby prevents to some extent the development of large-amplitude, high-frequency oscillations in the applied loading pulse.

In addition to the two key measurements, from which the vertical stress and the vertical strain in the specimen are determined, there are a number of measurements which can be made when desired to provide certain support-type information (Figs. 85 and 86). The flush-mounted pressure transducer and LVDT 0 (represented by Instrumentation Channels 5 and 1, respectively, in Fig. 85) are used to obtain the two key measurements. The strain-gage elements bonded to the outside periphery of the soil container are used to provide an indication of the lateral specimen stress (Channel 7). The three LVDT's other than LVDT 0 (Channels 2, 3, and 4), when located at distances of 2, 3, and 4 in. from the center of the specimen as shown in Fig. 81, can be used to evaluate the effect of sidewall friction on various portions of the specimen, since they measure the displacement of the specimen surface at several points on the surface. If the coils of one of these LVDT's is placed inside the base of the soil container (in the position occupied by the lower accelerometer) and the coils of either of the other two LVDT's is left in the position shown in Fig. 81, the pair of LVDT's can be used to measure equipment compressibility directly (by

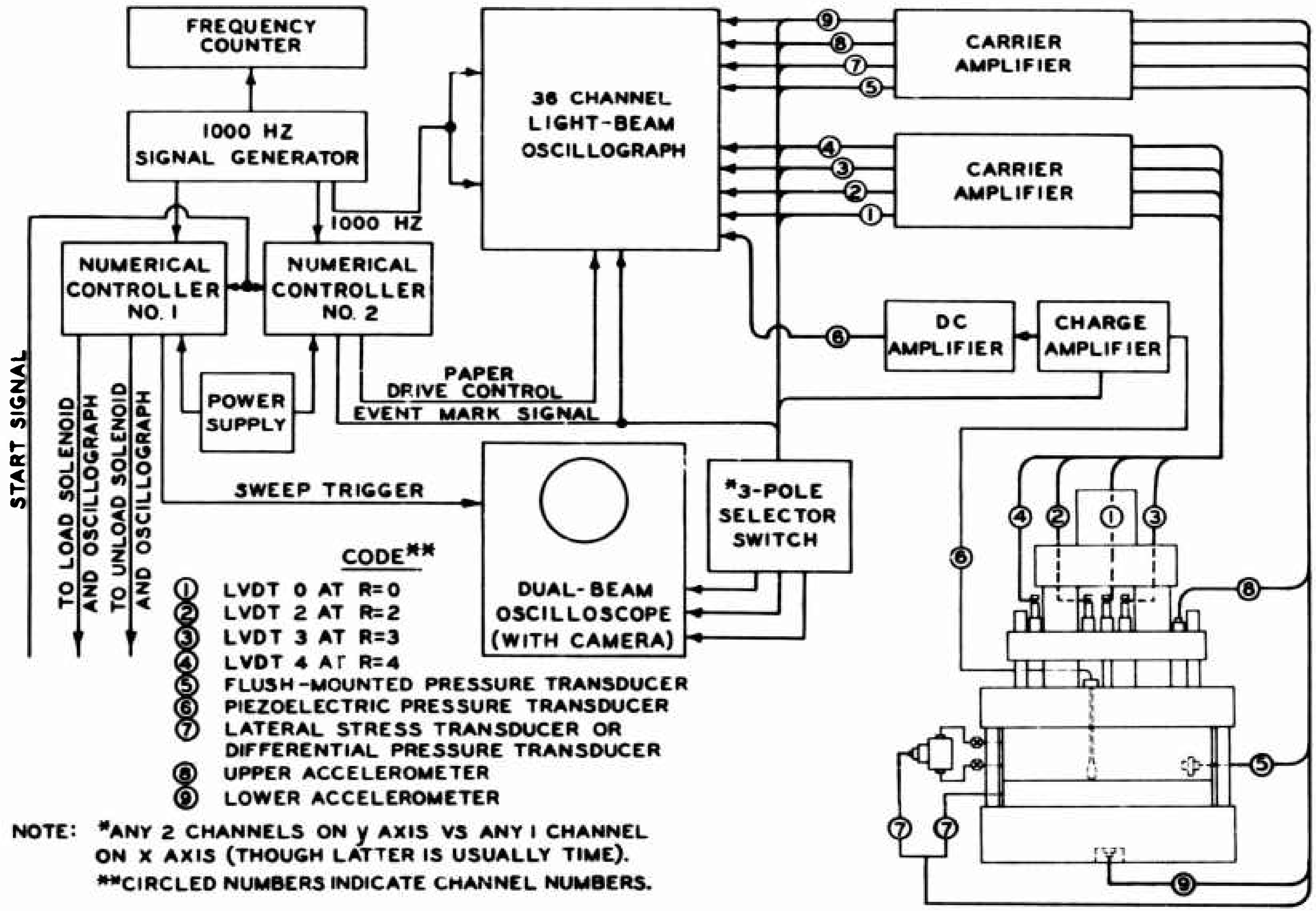


Fig. 85. Schematic drawing of measurement system.

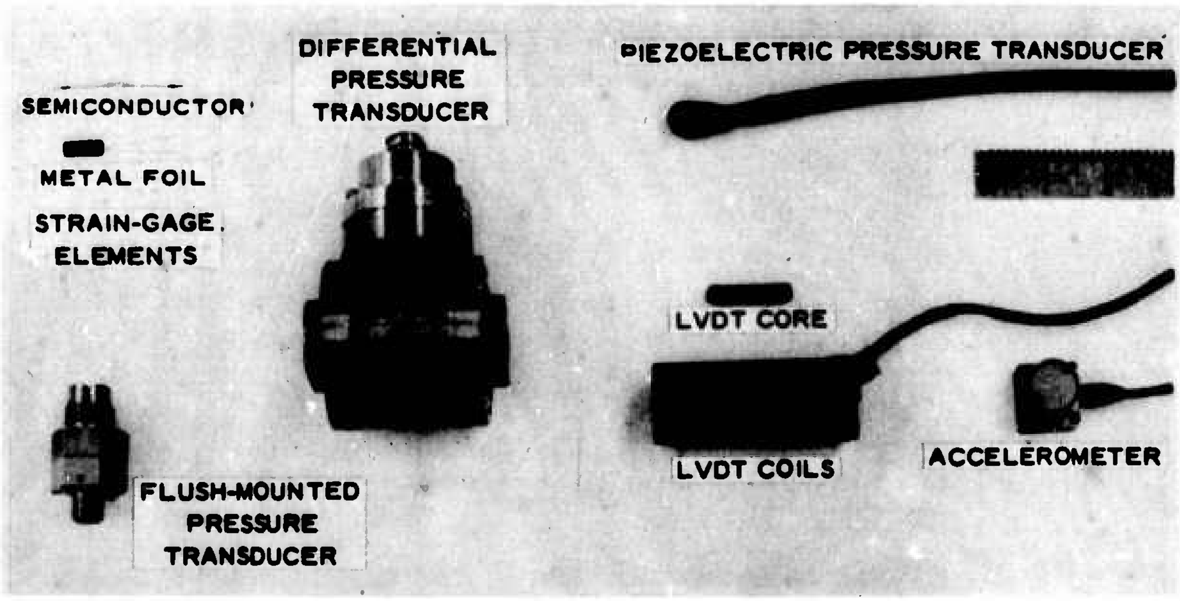


Fig. 86. Electromechanical transducers.

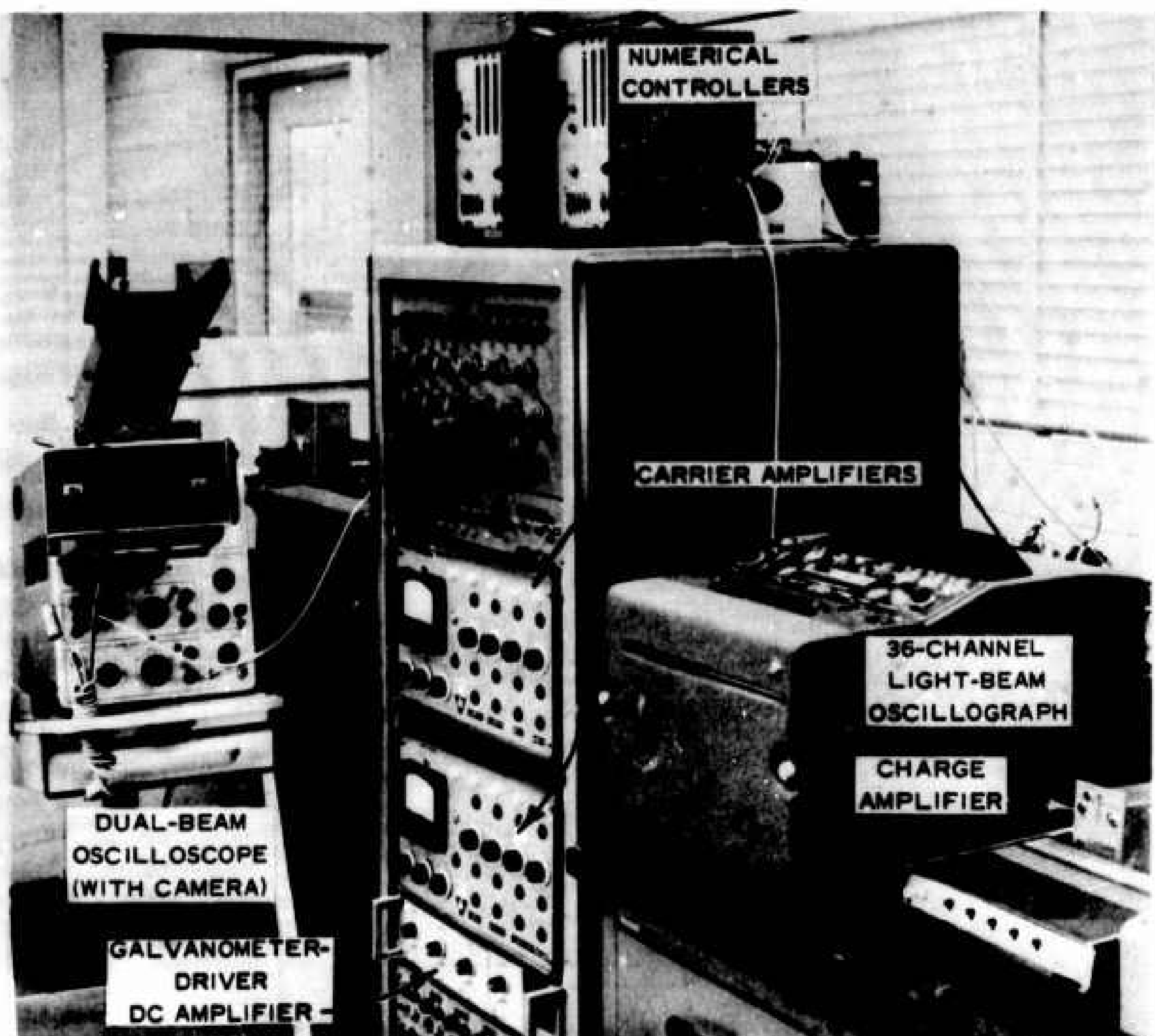


Fig. 87. Instrumentation room.

attaching the cores of both these LVDT's to a fixed reference). The piezo-electric pressure transducer (Channel 6), which is located in the pressure fluid in the vicinity of the center of the specimen (Fig. 81), can be used either to establish the presence or absence of high-frequency components during tests of very short duration or as a check or support measurement for the flush-mounted pressure transducer. The differential pressure transducer (Channel 7) is used to supplement the flush-mounted pressure transducer during tests which involve a fairly large simulated overburden pressure relative to the applied overpressure, in order to improve the accuracy of the pressure measurement; the differential pressure transducer measures the applied overpressure directly, as the difference between the total pressure and the overburden-simulating initial pressure. (The two accelerometers, Channels 8 and 9, were used during the facility-evaluation program, but they are not generally required otherwise.)

An indication of the experimental accuracy of the data for any particular test is obtained by evaluating the various individual contributions to the experimental error for that test and determining their cumulative effect. The factors from which the individual contributions stem include specimen disturbance during equipment assembly and test preparation, side-wall friction, nonuniform loading conditions, equipment compressibility, lateral specimen strain, nonlinearity of transducer response, nonrepeatability of transducer response, drift in the transducer signal, frequency-response limitations in transducer response, signal-resolution limitations, and mismatch at the LVDT disc-specimen interface. It is estimated that the data obtained for 70 percent of the routine-type tests conducted are accurate to ±7 percent (of the peak value of the quantity of interest) or

better, and the data obtained for 70 percent of the precision-type tests conducted are accurate to ±3 percent or better.

Although there are a few limitations associated with the general-purpose, one-dimensional compression test facility which has been developed at WES, there do not appear to be any serious obstacles preventing their elimination. The three limitations considered to be most important concern the peak-pressure capability, the oscillations in the loading portion of the applied pulse, and the seating of tube-contained specimens. The Dynapak loader currently being used has an effective peak-load capability of only 25 kips, which limits the peak-pressure capability of the one-dimensional-compression test facility to approximately 300 psi when a 10-in.-diam soil chamber is used. Current requirements are for a peak-pressure capability of approximately 1000 psi, and an even higher capability is considered to be necessary to meet anticipated future requirements. There are a number of possible approaches to the elimination of the peak-pressure-capability limitation, the most promising of which appears to be the development of a higher-capacity dynamic loading machine of the Dynapak type. Incorporation of a variable-mass load column in the higher-capacity loader would eliminate the major limitation associated with the oscillations in the loading portion of the applied pulse, the limitation on the fastest rise time which can actually be achieved. Seating of tube- (or ring-) contained specimens on the base of the soil chamber is a problem of concern, particularly for stiff specimens, because experience has shown that small imperfections in the end surface of the tube prevent the combined tube-specimen surface from mating with the base of the soil chamber at all points on their interface, thus introducing an error in the

measured specimen response. The most promising approach to the solution of the mismatch problem at the base of tube-contained specimens involves the use of a capping compound between the specimen and the base of the soil chamber.

5.2 Conclusions

Incorporation of the newly formulated piston-fluid loading technique in conjunction with the multiple-reflection testing technique in the design of the WES one-dimensional compression test facility has made it possible to develop a test facility which is characterized by greater versatility and better performance than could otherwise be achieved. Equipment of the type developed at WES can be used to conduct tests for purposes of fundamental research as well as for practical engineering applications, on either prepared or sampled specimens of all soil types, within a broad range of peak pressures and loading durations that is associated with nuclear-weapons-effects problems. The experimental-accuracy capability which can be achieved, both for precision-type research applications and for routine-type practical applications, approaches that beyond which an additional increase would not be generally useful.

Development of the WES test facility has resulted in an important step towards establishing the feasibility of using a single general-purpose device to determine the one-dimensional compression characteristics of soils subjected to nuclear-weapons-induced loadings for a broad range of material, loading, and application conditions. Since there do not appear to be any insurmountable problems associated with it, the WES test facility can be used as a basis for the development of a model, general-purpose,

one-dimensional compression test facility for nuclear-weapons-effects-related applications.

5.3 Recommendations

The overall success of the investigation described herein provides some justification for the additional investment in time and funds required to eliminate the most important of the limitations associated with the one-dimensional compression test facility developed at WES. Consequently, it is recommended that studies be initiated to determine (1) the feasibility of constructing a 100-kip dynamic loading machine, similar in principle to the Dynapak loader, which affords the opportunity for controlling (a) the characteristics of the applied load and (b) the mass of the load column which transmits the load to the device, and (2) the feasibility of using a capping compound to eliminate the mismatch between the bottom surface of a tube-contained specimen and the base of the soil chamber. It is further recommended that the comprehensive sidewall-friction study already planned be undertaken at the earliest possible opportunity, so that a better indication than is currently available of the experimental-accuracy capability of the test facility for small-diameter specimens can be obtained.

In addition to the efforts recommended above, which can be justified on the basis of clearly established program requirements at WES, there are a number of efforts which should be undertaken as time permits to extend the capability of the WES test facility in order to help meet anticipated future requirements. A study should be undertaken, for example, to determine the feasibility of using newly formulated concepts for applying a controlled, inpulse-type pressure pulse uniformly to a large (4-ft-diam) surface to

develop a high-capacity, ram-type dynamic loading machine with controlled loading characteristics. If feasible, an order-of-magnitude increase in capacity over currently available ram-type loaders could be achieved. Another effort which should be pursued is the extension of the measurement system to meet anticipated future requirements. It would be desirable to install and evaluate a transducer which could measure equipment compressibility directly for all tests. It would also be desirable to develop a technique for determining the lateral stress in the specimen for all tests without sacrificing the lateral constraint required for one-dimensional-compression conditions. Another addition to the measurement system likely to be useful in the future, particularly in connection with tests conducted for research applications, is a pore-pressure transducer; the associated capability for independently adjusting the pore pressure in a specimen is another desirable feature to be incorporated into the test facility.

There is one final recommendation which should be made in connection with the general-purpose, one-dimensional compression test facility developed at WES. The capability of the WES facility for providing reliable data in support of research-type applications has been demonstrated. It is extremely important that every effort be made to take advantage of this capability, particularly since the various innovations incorporated in the WES facility make it possible to obtain some important fundamental information which cannot be obtained elsewhere. Consequently, it is recommended that the various types of fundamental studies required (see, for example, Sections 1.2 and 4.6) be conducted whenever possible, and that the inevitable pressure to use the facility exclusively for routine-type tests in support of other activities be actively resisted.

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APPENDIX A

SUPPORTING COMPUTATIONS

A.1 Frequency Characteristics of Measured Signals

The Dynapak loader at WES was developed, and has been used, as a load generator for dynamic small-scale footing tests in the nuclear-weapons-effects research program (Cunny and Sloan, 1961). The data obtained during these tests (Jackson and Hadala, 1964; Hadala, 1965) indicate that, for very small column displacements (about 0.1 in.) and high loads (about 25 kips), a loading history similar to that shown in Fig. 88 can be anticipated at the base of the load column.

It is apparent that components of several frequencies are represented in the loading history, both in the rise and in the decay portions. For purposes of design--principally of the measurement system--and for convenience in discussion, it is desirable to refer to an upper-bound frequency for each of the portions of the actual loading history and to a pseudo-loading history which reflects the two upper-bound frequencies (Fig. 89). Clearly, the pseudo-loading history is such that substantially every level of load is reached and dissipated sooner (i.e., faster) than in the actual history.

Since, in the simulation of nuclear-weapons loadings, the rise portion of the loading history is always faster than the decay portion, it is sufficient for most purposes to consider only the rise portion of the data. On the one extreme, for long-duration tests conducted with the equipment assembled in the auxiliary configuration, the rise time of the applied loading pulse is likely to be measured in minutes. On the other extreme, for

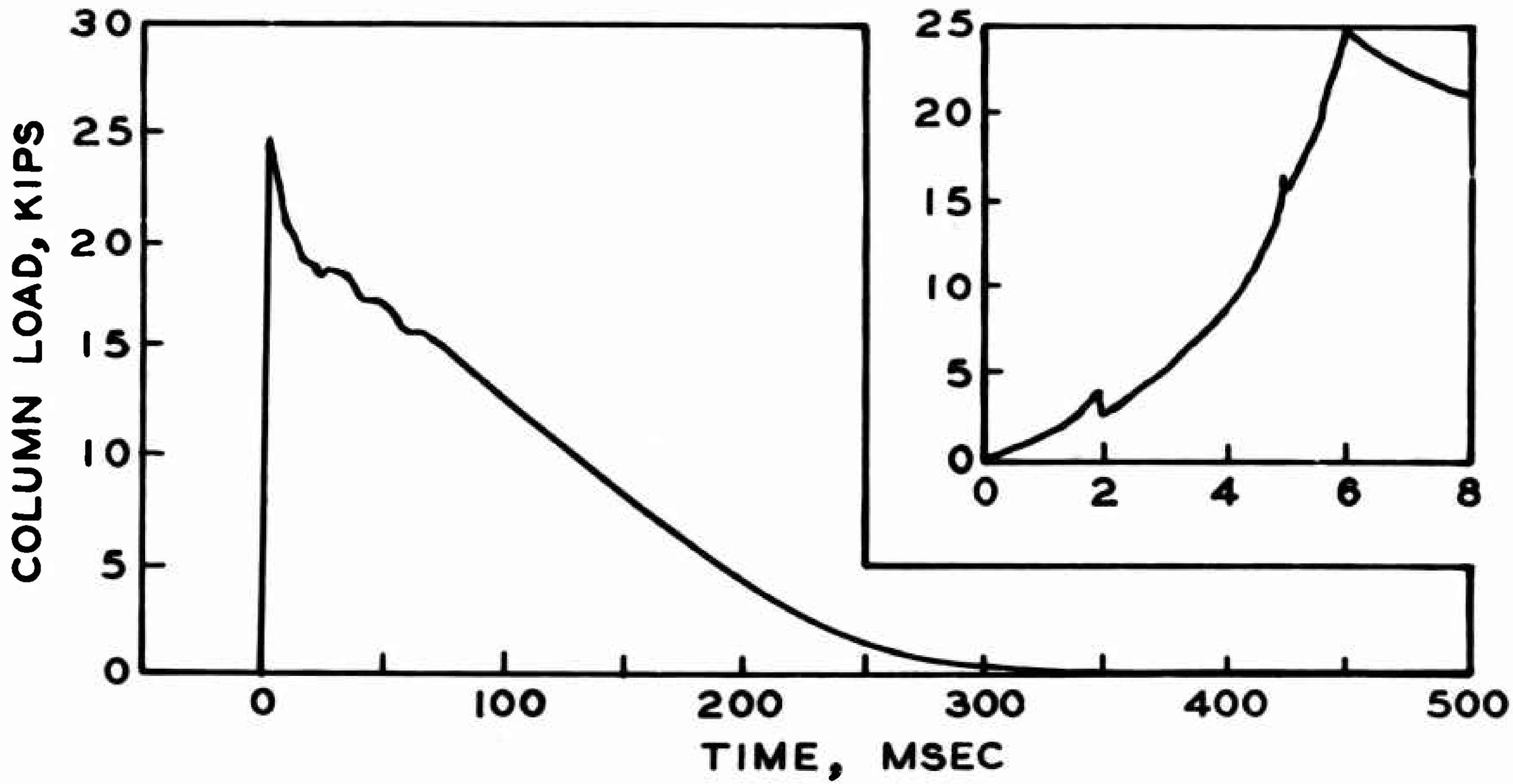
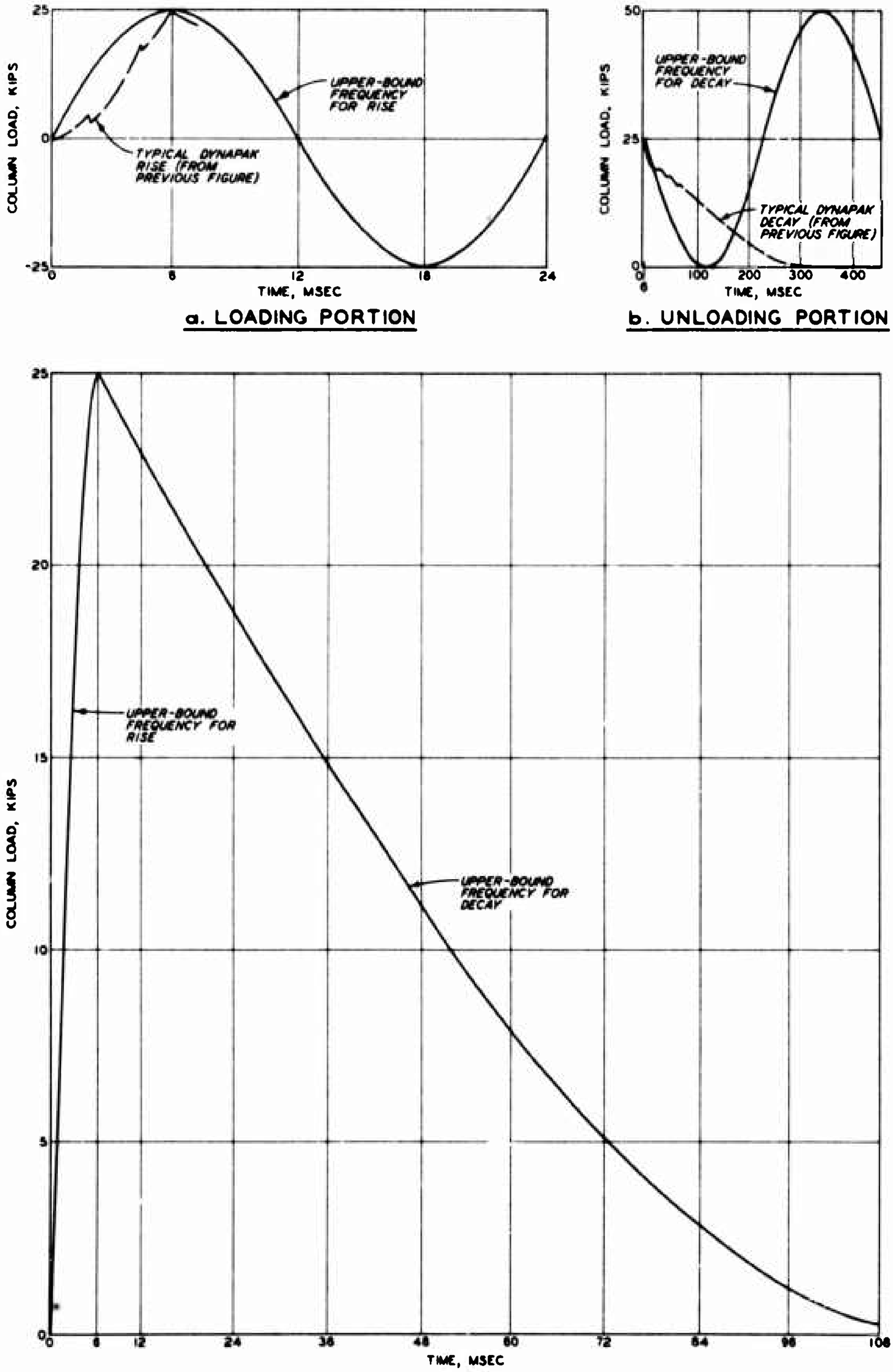


Fig. 88. Typical impulse-type load from Dynapak loader (from Jackson and Hadala, 1964).



a. LOADING PORTION

b. UNLOADING PORTION

c. COMPLETE PSEUDO-LOADING HISTORY

Fig. 89. Pseudo-loading history representation of typical Dynapak-generated pulse.

short-duration tests conducted with the equipment assembled in the principal configuration, the rise time is likely to be measured in milliseconds.

The fastest (i.e., shortest) rise time likely to be needed in the one-dimensional compression test program can be computed from the stated design specifications concerning accuracy of the data and range of specimen stiffness, in accordance with Equation 2.1. The stiffest specimen designed for is one with a constrained modulus of 200,000 psi, and the thinnest specimen likely to be used is one that is 1 in. thick. The minimum unit weight for a specimen with a 200,000 psi constrained modulus is probably about 100 pcf. Consequently:

for a given test

$$(t_r)_{min} = \frac{100}{\Delta}\frac{L}{c} = \frac{100}{\Delta} L \sqrt{\frac{\rho}{M}} = \frac{100}{\Delta} L \sqrt{\frac{\gamma}{gM}}$$

for the entire test program

$$(t_r)_{min} = \frac{100}{\Delta} (L)_{min} \sqrt{\frac{(\gamma)_{min}}{g(M)_{max}}}$$

$$(t_r)_{min} = \frac{100}{1} (1) \sqrt{\frac{100}{1728 \times 200{,}000 \times 386}}$$

$$(t_r)_{min} = 100 \quad \sqrt{7.50 \times 10^{-10}} \approx 3 \times 10^{-3} \text{ sec} \approx 3 \text{ msec}$$

No value has been specified for the minimum rise time to be achieved. The computation above simply establishes a lower bound for the rise time, in that, even if it were possible to achieve rise times faster than 3 msec, such fast loading rates would not be useful in the one-dimensional compression test program.

It is apparent from Fig. 89 that the period associated with the upper-bound frequency for the rise portion of the loading history is simply 4 times the rise time. Consequently, the maximum upper-bound frequency for the measured signals in the one-dimensional compression test facility--corresponding to a minimum rise time of 3 msec--is 1 cycle per 12 msec, or approximately 80 cps. The minimum upper-bound frequency is 1 cycle per several minutes, or approximately 0 cps.

In summation, then, the frequency range of the signals to be measured in the one-dimensional compression test program can be considered to be 0-80 cps. The minimum rise time likely to be needed is 3 msec.

A.2 Specimen Geometry

It is well known that the effect of sidewall friction on the stress and strain distribution within a one-dimensional compression specimen is complex and not readily subject to rigorous analysis. Consequently, if one wishes to determine the magnitude of the experimental error which results from sidewall-friction effects accurately, one should attempt to accomplish this experimentally.

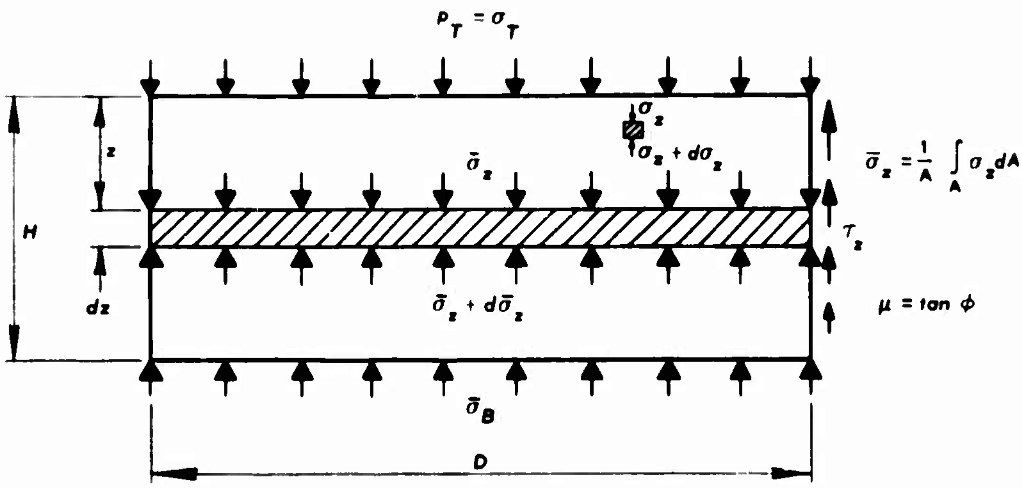
Provisions were made in the WES one-dimensional compression device for experimentally evaluating the effect of sidewall friction (see Section 3.6). Although the fairly comprehensive experimental evaluation program designed to study sidewall-friction effects has yet to be conducted, the data obtained in the overall facility-evaluation program indicate that the trial specimen geometry selected during the design of the device will probably meet the accuracy specifications for most specimens of interest (see Section 4.5). Final selection of the specimen geometry will be accomplished

when the sidewall-friction study is completed and the results analyzed.

Selection of the trial specimen geometry was based on several considerations (Section 3.3), among which were the results of some computations based on a technique commonly used and accepted in the conventional soil mechanics literature. The technique, which is based on the work of Taylor (1942), has been used by others in connection with one-dimensional compression devices designed for nuclear-weapons-effects studies (Hendron, 1963; Abbott, 1965). The derivations of the governing relationships and the computations made in support of the design of the WES device are shown in Fig. 90.

The relationship which is derived in Fig. 90 is based on two important assumptions: (1) that slippage occurs at the soil-sidewall interface in accordance with the Mohr-Coulomb condition of $\tau_{max} = \sigma_n \tan \phi$, and (2) that the normal stress between the soil and the sidewall (σ_n) at any depth z in the specimen is directly proportional to the average vertical stress at that depth. The first assumption is probably a fair representation of reality for cohesionless specimens. The second assumption is not accurate, because the normal stress between the soil and the sidewall is known to be proportional to the vertical stress at the wall and not to the average vertical stress. If it is assumed, however, that the ratio between the vertical stress at the soil-sidewall interface at any depth and the average vertical stress at that depth is nearly constant, then it can be concluded that the relationship shown is indicative of the actual physical situation, even if only on a qualitative basis.

The relationship derived in Fig. 90 clearly shows the importance of specimen geometry on the sidewall-friction effect. Even if the measurement



a. SKETCH OF SOIL SPECIMEN

ASSUME FRICTION OVERCOME AT SIDEWALL:

$$\tau_z = \tau_{max} = \bar{\sigma}_z K_o \mu$$

$$(d\bar{\sigma}_z)\left(\frac{\pi}{4} D^2\right) + (\tau_z)(\pi D)\, dz = 0$$

$$d\bar{\sigma}_z = -\frac{4\bar{\sigma}_z K_o \mu}{D} dz$$

$$\frac{d\bar{\sigma}_z}{\bar{\sigma}_z} = -\frac{4K_o\mu}{D} dz$$

$$\ln \bar{\sigma}_z = -\frac{4K_o\mu}{D} z + \ln p_T$$

$$(\ln \bar{\sigma}_z - \ln p_T) = -\frac{4K_o\mu}{D} z$$

$$\frac{\bar{\sigma}_z}{p_T} = e^{-4K_o \mu (z/D)}$$

$$\frac{\bar{\sigma}_B}{p_T} = e^{-4K_o \mu (H/D)}$$

b. DERIVATION OF GOVERNING RELATIONSHIP

I. ASSUME $\frac{H}{D} = \frac{1}{4}$ AND $(K_o\mu) = 0.2$

$$\frac{\bar{\sigma}_B}{p_T} = e^{-(4)(0.2)(0.25)}$$

$$\frac{\bar{\sigma}_B}{p_T} = 0.82$$

AVG FRICTION LOSS $= \frac{1 - 0.82}{2} = 9\%$

II. ASSUME $\frac{H}{D} = \frac{1}{10}$ AND $(K_o\mu) = 0.2$

$$\frac{\bar{\sigma}_B}{p_T} = e^{-(4)(0.2)(0.1)}$$

$$\frac{\bar{\sigma}_B}{p_T} = 0.92$$

AVG FRICTION LOSS $= \frac{1 - 0.92}{2} = 4\%$

III. ASSUME $\frac{\bar{\sigma}_B}{p_T} = 0.98$ AND $(K_o\mu) = 0.2$

$$\ln 0.98 = -(4)(0.2)(H/D)$$

$$\frac{D}{H} = \frac{0.8}{0.02} = 40$$

c. SPECIFIC COMPUTATIONS

Fig. 90. Effect of sidewall friction on overall specimen.

system were designed to observe the behavior of the specimen as a whole, as is ordinarily done for piston-loading devices (Section 2.3), the average vertical stress on any horizontal plane through the specimen ($\bar{\sigma}_z$) would be very nearly equal to the applied pressure or stress (p_T) for a specimen with a large diameter-to-thickness ratio (D/H). According to the relationship shown, sidewall friction probably does not reduce the average vertical stress in a one-dimensional compression specimen by more than 9 percent for the conventional diameter-to-thickness ratio of 4. For the diameter-to-thickness ratio of 10 selected for the WES device, the average vertical stress is probably not reduced by more than 4 percent. It is interesting to note that a diameter-to-thickness ratio of approximately 40 would be required to assure a friction loss of less than 1 percent, as specified for the WES device.

It is important to recognize that the computations discussed above are applicable for devices in which the measurement system is designed to observe the behavior of the specimen as a whole. The results of such computations represent upper-bound values to the sidewall-friction effect on a specimen in a fluid-loading device, where the behavior observed is limited to the central portion of the specimen only (where sidewall-friction effects are least severe). Clearly, the conditions near the center of the specimen in a fluid-loading device are more nearly representative of the state of one-dimensional compression than are the conditions near the vertical-shear-inducing sidewall. If it is assumed that each soil particle in the specimen transmits a shear stress to a single lateral neighboring particle only, then it must be concluded that the effect of sidewall friction is transmitted along a 45-deg angle, as shown in Fig. 91. For a

10-in.-diam, 1-in.-thick specimen, therefore, the central area corresponding to a diameter of 8 in. will remain unaffected by sidewall friction. Since the diameter of the displacement-sensing disc in the WES device is less than 2 in., there appears to be sufficient reason to believe that the portion of the specimen observed will be relatively unaffected by sidewall friction. In fact, if the sidewall-friction effect is transmitted along a 45-deg angle, as assumed, then diameter-to-thickness ratios even less than the 4 in common use could be used with satisfactory results for fluid-loaded specimens if the dimensions of the specimen were large in absolute magnitude (as in the WES device).

There has been only one attempt, to the knowledge of the author, to examine analytically the effect of sidewall friction on the measurements obtained during a test in a fluid-loading device (Abbott, 1965). The effort was of a cursory nature, and unfortunately the results obtained are open to question. Abbott assumed the vertical shear stress (τ) at some radial location (r) and depth (z) to be related to the vertical shear stress at the sidewall (τ_{max}) at that depth by the relationship $\tau = \left(\frac{r}{R}\right)^n \tau_{max}$. By isolating a small part of the specimen at its center for analysis, he derived the following relationship:

$$\frac{\bar{\sigma}_z}{p_T} = 1 + \left(\frac{d}{D}\right)^n \left[e^{-4K_o\mu(z/D)} - 1\right] \tag{A.1}$$

where $\bar{\sigma}_z$ is the average vertical stress on the part of the specimen isolated, and d is twice the radius (r) of that part of the specimen. (The other symbols are as defined above and in Fig. 90.) As Abbott himself later recognized, Equation A.1 is slightly in error, the correct relationship being that shown in Equation A.2.

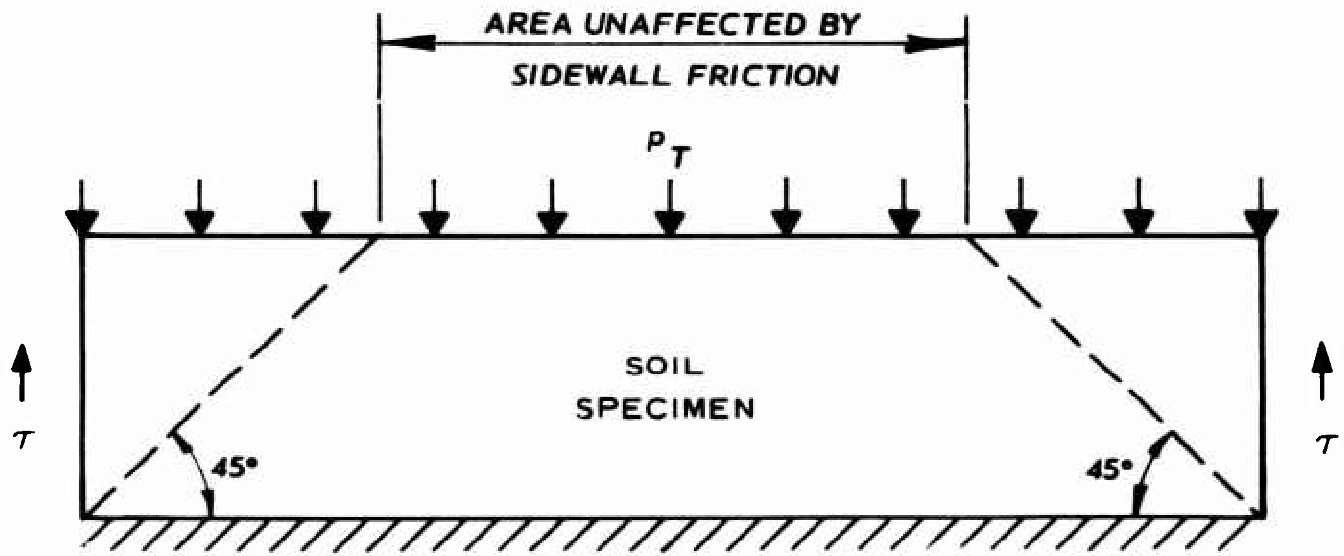


Fig. 91. Sketch depicting probable extent of sidewall-friction effect.

$$\frac{\bar{\sigma}_z}{p_T} = 1 + \left(\frac{d}{D}\right)^{n-1} \left[e^{-4K_o\mu(z/D)} - 1\right] \tag{A.2}$$

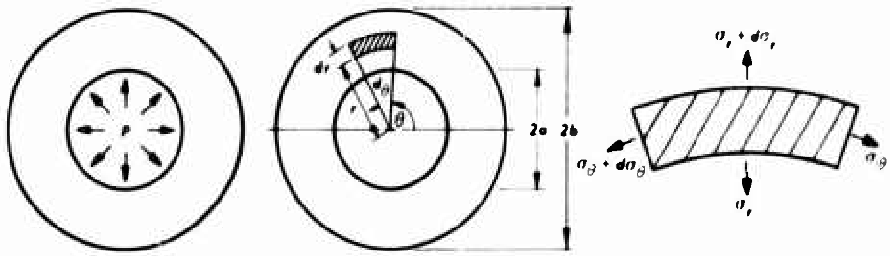
In spite of the apparent soundness of Abbott's approach, the relationship shown (Equation A.2) is physically invalid for positive values less than or equal to unity. It is hoped that the comprehensive sidewall-friction study that is to be conducted with the WES device will provide the data needed to understand sidewall-friction effects on fluid-loaded, one-dimensional compression specimens.

A.3 Thickness of Soil Constraining Ring

The selection of a thickness for the soil constraining ring in the WES one-dimensional compression device was based on three considerations: (1) the behavior of a thick-walled steel ring, (2) the effect of lateral soil strain on the modulus determined, and (3) the design specification concerning experimental accuracy.

Although various aspects of the elasticity solution for the thick-walled ring or thick-walled cylinder problem are adequately treated in the literature, those aspects of the solution which are pertinent to the design and evaluation of the WES one-dimensional compression device are summarized for convenience in Figs. 92 and 93.

The effect of lateral soil strain on the modulus determined from the two key measurements in a one-dimensional compression test cannot be predicted accurately at the present time (1968), since the general constitutive behavior of particulate materials is not well understood. However, it is reasonable to assume that if the magnitude of the lateral soil displacement does not exceed the average particle (or particle-cluster) dimension in the specimen, the effect of lateral soil strain on the modulus determined



a. FREE-BODY SKETCHES

EQUILIBRIUM

$$\Sigma F_r = 0 = (\sigma_r)(r d\theta) - \left(\sigma_r + \frac{\partial \sigma_r}{\partial r} dr\right)(r + dr)\, d\theta + (\sigma_\theta)(dr)\left(\frac{d\theta}{2}\right) + \left(\sigma_\theta + \frac{\partial \sigma_\theta}{\partial \theta} d\theta\right)(d_r)\left(\frac{d\theta}{2}\right)$$

$$\frac{\partial \sigma_r}{\partial r} = \frac{d\sigma_r}{dr} \quad \text{AND} \quad \frac{\partial \sigma_\theta}{\partial \theta} = 0 \quad \text{BY SYMMETRY}$$

$$\sigma_\theta - \sigma_r - r\frac{d\sigma_r}{dr} = 0 \quad \text{NEGLECTING THE HIGHER ORDER TERM}$$

$$\Sigma F_\theta \equiv 0 \quad \text{BY SYMMETRY}$$

COMPATIBILITY

$$\epsilon_r = \frac{\left(u + \frac{du}{dr} dr\right) - u}{dr} = \frac{du}{dr} \quad \text{AND} \quad \epsilon_\theta = \frac{2\pi(r + u) - 2\pi r}{2\pi r} = \frac{u}{r}$$

CONSTITUTIVE

$$\epsilon_r = \frac{1}{E}(\sigma_r - \nu\sigma_\theta) \quad \text{AND} \quad \epsilon_\theta = \frac{1}{E}(\sigma_\theta - \nu\sigma_r)$$

$$\sigma_r = \frac{E}{1 - \nu^2}(\epsilon_r + \nu\epsilon_\theta) \quad \text{AND} \quad \sigma_\theta = \frac{E}{1 - \nu^2}(\epsilon_\theta + \nu\epsilon_r)$$

b. KEY RELATIONSHIPS

$$\sigma_\theta - \sigma_r - r\frac{d\sigma_r}{dr} = 0$$

$$\frac{E}{1-\nu^2}\left[\frac{u}{r} + \nu\frac{du}{dr}\right] - \frac{E}{1-\nu^2}\left[\frac{du}{dr} + \nu\left(\frac{u}{r}\right)\right] - r\frac{E}{1-\nu^2}\left[\frac{d^2u}{dr^2} + \nu\left(-\frac{u}{r^2}\right) + \frac{\nu}{r}\left(\frac{du}{dr}\right)\right] = 0$$

$$\frac{d^2u}{dr^2} + \frac{1}{r}\frac{du}{dr} - \frac{u}{r^2} = 0$$

c. GOVERNING DIFFERENTIAL EQUATION

$$@\ r = a:\ \sigma_{ra} = -p \quad \text{AND} \quad @\ r = b\ \ \sigma_{rb} = 0$$

d. BOUNDARY CONDITIONS

Fig. 92. Elasticity solution for thick-walled cylinder; basic equations.

ASSUMING $u = \sum a_n r^n$ YIELDS A SOLUTION OF THE FORM $u = a_1 r + a_{-1} r^{-1}$

$$u = Ar + Br^{-1}$$

$$\epsilon_r = A - Br^{-2} \qquad \text{AND} \qquad \epsilon_\theta = A + Br^{-2}$$

$$\sigma_r = \frac{E}{1-\nu^2}\left(A - Br^{-2} + \nu A + \nu B r^{-2}\right) = E\left[\frac{A}{1-\nu} - \frac{B}{r^2(1+\nu)}\right]$$

$$@\ r = a : \sigma_{ra} = -p \qquad \text{AND} \qquad @\ r = b : \sigma_{rb} = 0$$

$$A = \left(\frac{1-\nu}{E}\right)\left(\frac{pa^2}{b^2 - a^2}\right) \qquad \text{AND} \qquad B = \left(\frac{1+\nu}{E}\right)\left(\frac{pa^2 b^2}{b^2 - a^2}\right)$$

$$u = \left(\frac{p}{E}\right)\left(\frac{a^2}{b^2 - a^2}\right)(r)\left[(1-\nu) + (1+\nu)\frac{b^2}{r^2}\right]$$

$$\epsilon_r = \left(\frac{p}{E}\right)\left(\frac{a^2}{b^2 - a^2}\right)\left[(1-\nu) - (1+\nu)\frac{b^2}{r^2}\right] \qquad \text{AND} \qquad \epsilon_\theta = \left(\frac{p}{E}\right)\left(\frac{a^2}{b^2 - a^2}\right)\left[(1-\nu) + (1+\nu)\frac{b^2}{r^2}\right]$$

$$\sigma_r = \frac{pa^2}{b^2 - a^2}\left(1 - \frac{b^2}{r^2}\right) \qquad \text{AND} \qquad \sigma_\theta = \frac{pa^2}{b^2 - a^2}\left(1 + \frac{b^2}{r^2}\right)$$

a. SOLUTION FOR GENERAL RELATIONSHIPS

SOIL SPECIMEN LATERAL STRAIN (u_a/a)

$$\frac{u}{a} = \left(\frac{p}{E}\right)\left(\frac{a}{b^2 - a^2}\right)(r)\left[(1-\nu) + (1+\nu)\frac{b^2}{r^2}\right]$$

$$\frac{u_a}{a} = \frac{p}{E}\left[\left(\frac{b^2 + a^2}{b^2 - a^2}\right) + \nu\right]$$

OUTSIDE CIRCUMFERENTIAL RING STRAIN ($\epsilon_{\theta b}$)

$$\epsilon_{\theta b} = \frac{p}{E}\left(\frac{2a^2}{b^2 - a^2}\right)$$

INSIDE AND OUTSIDE RADIAL RING DISPLACEMENT (u_a AND u_b)

$$u_a = \frac{p}{E}(a)\left[\left(\frac{b^2 + a^2}{b^2 - a^2}\right) + \nu\right] \qquad \text{AND} \qquad u_b = \frac{p}{E}\left(\frac{2a^2 b}{b^2 - a^2}\right)$$

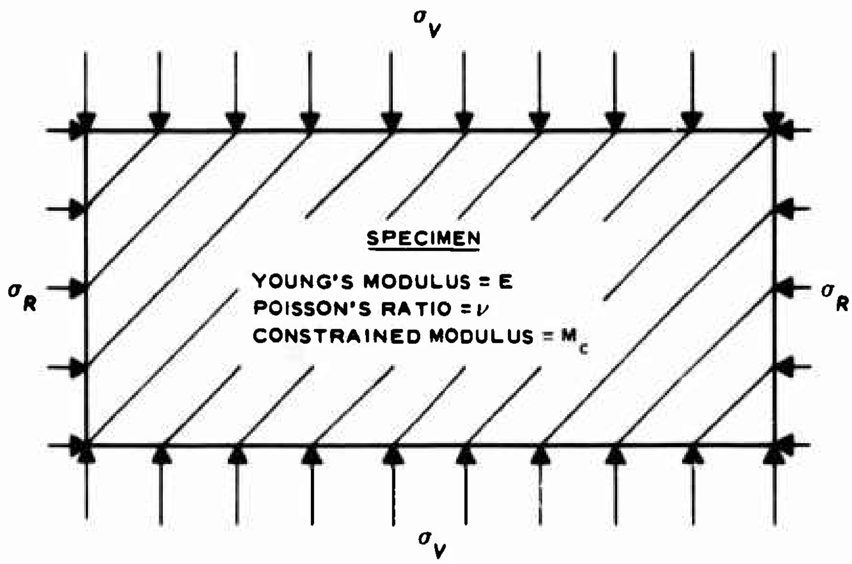
b. SOLUTION FOR PARTICULAR RELATIONSHIPS OF INTEREST

Fig. 93. Elasticity solution for thick-walled cylinder; solution of basic equations.

does not exceed the effect computed on the basis of elasticity theory. The derivation of the governing equation relating the error in constrained modulus to the amount of lateral strain permitted in an elastic specimen is shown in Fig. 94, and a plot of the equation is presented in Fig. 95.

It is clear from Fig. 95 that if the magnitude of the lateral specimen strain is not restricted to 1 percent (or less) of the magnitude of the vertical specimen strain, the 1 percent accuracy specified for each contribution to the experimental error will not be satisfied for a number of specimens of interest. Consequently, in the design of the constraining ring, the lateral strain was set equal to 1 percent of the vertical strain. In order that the design consider the worst likely condition, the vertical strain was set equal to 5×10^{-3}, corresponding to a vertical stress of 1000 psi on a specimen with a modulus of 200,000 psi (see Section 3.1), and the lateral soil stress (p in this analysis) was set equal to 500 psi. The design computations are shown in Fig. 96, and the anticipated error in constrained modulus for various specimens of interest is plotted in Fig. 97.

It should be noted that the lateral soil stress should have been set equal to 1000 psi to represent the worst possible condition. However, any value greater than 500 psi was considered to be unduly conservative for nearly all the stiff, laboratory-prepared specimens likely to be of interest. In fact, the only type of specimen which can be expected to be very stiff and still have a high Poisson's Ratio is a very nearly saturated material (see Section 2.1), and this type of material is far more likely to be prepared in a ring than in the soil chamber itself. (For maximum parameter control, preparation convenience, and testing accuracy, a material of this type should be prepared in a small-diameter ring,



CONSTITUTIVE RELATIONS:

$$\epsilon_R = \frac{1}{E}\left[\sigma_R (1-\nu) - \nu\sigma_V\right]$$

$$\epsilon_V = \frac{1}{E}\left[\sigma_V - 2\nu\sigma_R\right]$$

LETTING $\alpha = \dfrac{\epsilon_R}{\epsilon_V}$:

$$\alpha\epsilon_V E = \sigma_R (1-\nu) - \nu\sigma_V$$

$$\epsilon_V E = -2\nu\sigma_R + \sigma_V$$

SOLVING FOR σ_V:

$$\sigma_V (1 - \nu - 2\nu^2) = \epsilon_V E (1 - \nu + 2\nu\alpha)$$

$$\sigma_V = \epsilon_V E \frac{1 - \nu + 2\nu\alpha}{(1-2\nu)(1+\nu)}$$

THE MEASURED MODULUS:

$$M = \frac{\sigma_V}{\epsilon_V} = E\frac{1-\nu}{(1-2\nu)(1+\nu)} + E\frac{2\nu\alpha}{(1-2\nu)(1+\nu)}$$

$$M = M_c + M_c\left(\frac{2\nu\alpha}{1-\nu}\right) = M_c\left(1 + \frac{2\nu\alpha}{1-\nu}\right)$$

PERCENT ERROR IN M_c:

$$\Delta = (100)\left|\frac{M_c - M}{M_c}\right| = 200\,\frac{\nu}{1-\nu}\,|\alpha|$$

Fig. 94. Derivation of equation showing effect of lateral strain on measured constrained modulus.

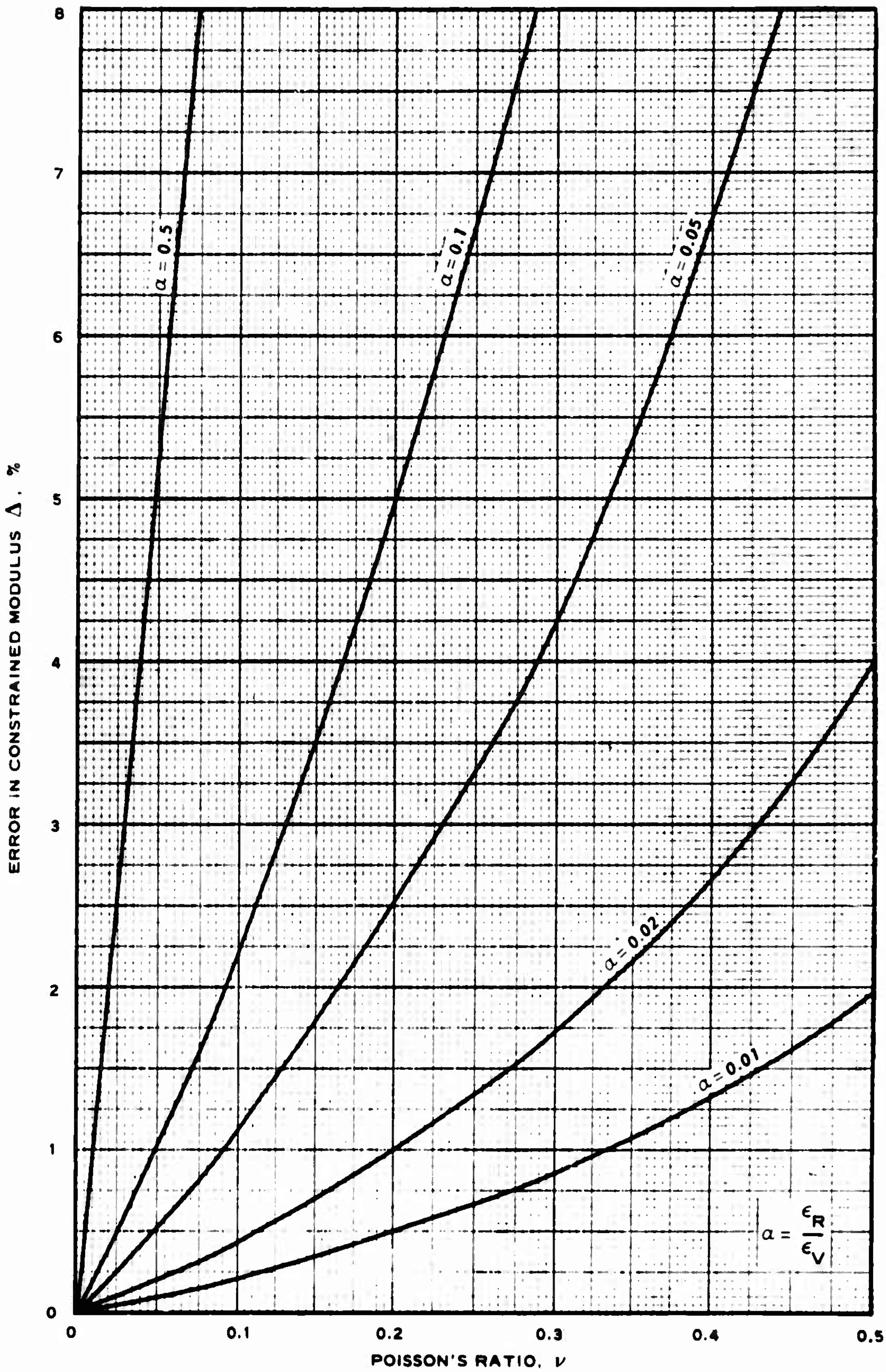
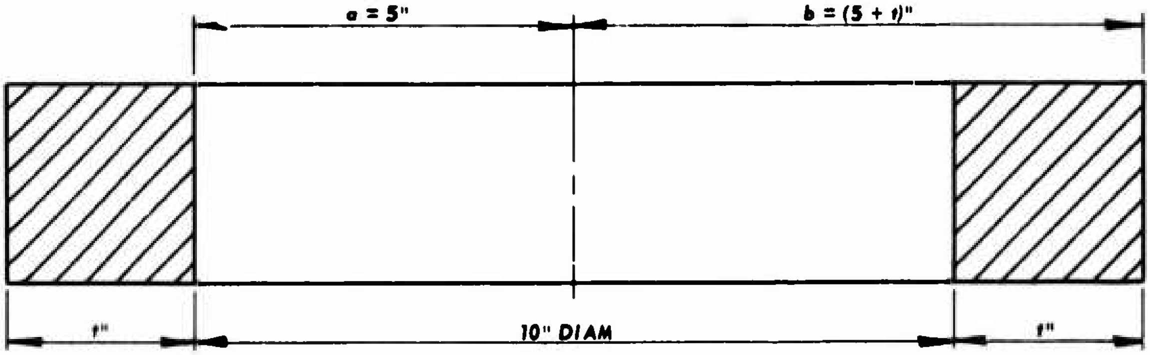


Fig. 95. Effect of lateral strain on measured constrained modulus.



$$\text{LATERAL SOIL STRAIN} = \epsilon = \frac{p}{E}\left\{\left[\frac{(a+t)^2 + a^2}{(a+t)^2 - a^2} + \nu\right]\right\}$$

$$t^2 + 2at - \frac{2a^2 p}{E\epsilon - (1+\nu)p} = 0$$

$$t^2 + (2)(5)(t) - \frac{(2)(25)(500)}{(30 \times 10^6)(5 \times 10^{-5}) - (1 + 0.3)(500)} = 0$$

$$t^2 + 10t - 29.4 = 0$$

$$t = 2.39 \text{ INCHES}$$

THICKNESS OF CONSTRAINING RING SELECTED = 2.5 INCHES

Fig. 96. Computations in support of design of soil constraining ring.

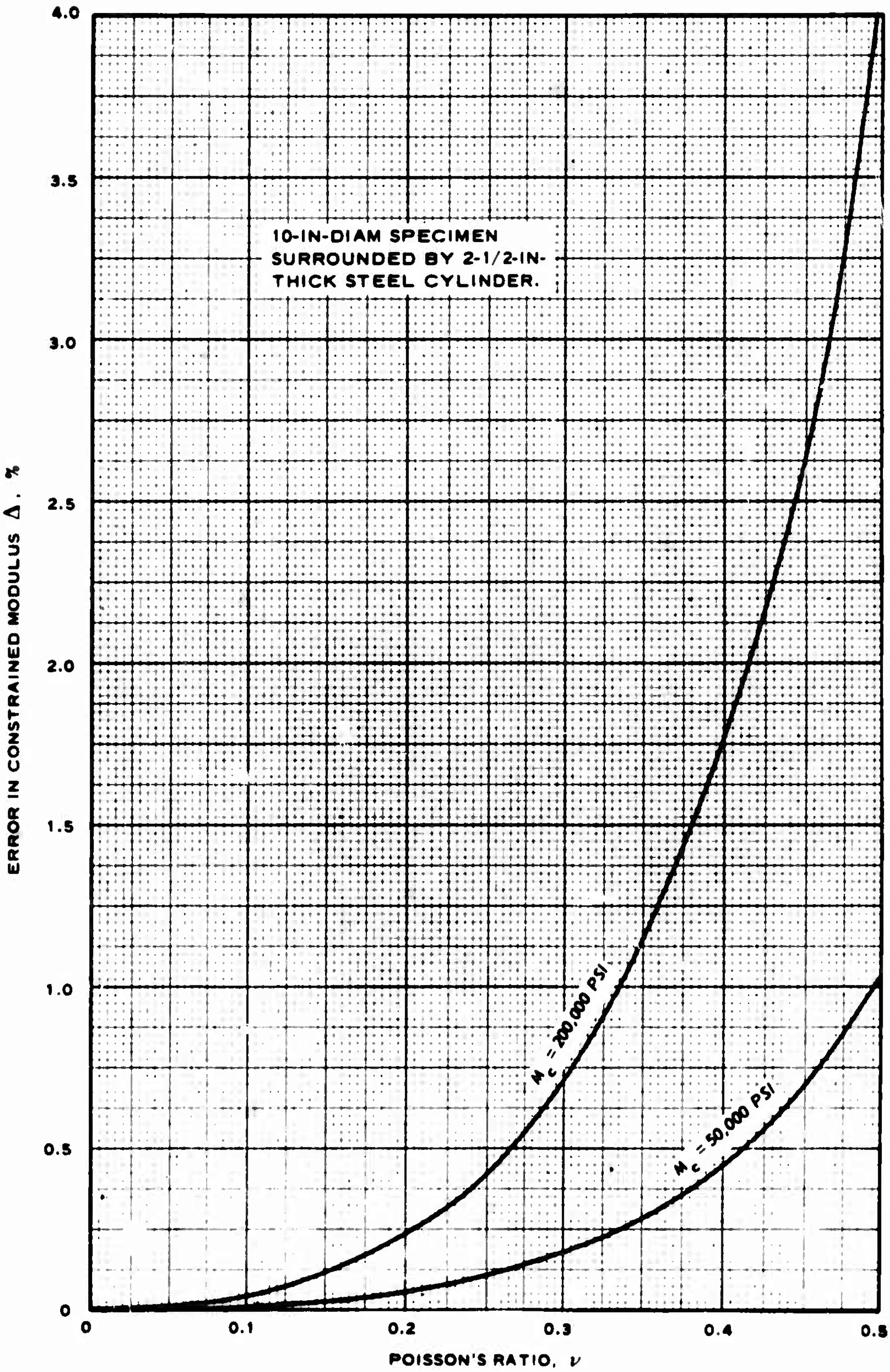


Fig. 97. Anticipated error in constrained modulus for various specimens of interest.

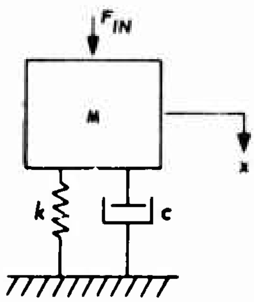
which is then placed in the center of the soil chamber and surrounded by a rubber membrane and water.)

A.4 Frequency-Response Characteristics of Measurement System

The frequency-response characteristics of each of the transducers, amplifier units, and recording units considered for use in conjunction with the WES one-dimensional compression device were evaluated to determine if the unit was capable of responding to the fastest input signals anticipated within the limitations imposed by the design specification concerning accuracy. The techniques used are outlined herein, with specific reference to the two key-measurement transducers and the amplifier-recorder system actually selected (Section 3.6).

A standard single-degree-of-freedom analysis (Fig. 98) was conducted to evaluate the frequency-response characteristics of the flush-mounted pressure transducer and the light-beam-oscillograph galvanometer, the latter being the limiting factor within the amplifier-recorder system (see Section 3.6). The mechanical behavior of each of these units is relatively simple (see Section 4.5), so that a damped single-degree-of-freedom system represents a fairly accurate physical description of the actual behavior.

The results of the analysis in Fig. 98 show that inertia of an element in the measurement system may affect the accuracy of the measurement in two distinct ways: (1) by causing an increase or decrease in the amplitude of the measured signal; and (2) by delaying the time at which any particular portion of the signal is observed. A plot of the former effect, generally referred to as amplitude overshoot (overregistration), amplitude undershoot (underregistration), or simply amplitude ratio or amplification,



$x(0) = \dot{x}(0) = 0$

DEFINITIONS

$F_{IN} = F_{ACTUAL}$

$\omega_n = \sqrt{k/M}$

$h = \frac{c}{c_{CR}} = \frac{c}{2\omega_n M}$

$\phi = \tan^{-1} \frac{2h\beta}{1-\beta^2}$

$F_{SPRING} = kx = F_{MEASURED}$

$\beta = \omega/\omega_n$

$\gamma = \sqrt{\frac{1}{(1-\beta^2)^2 + (2h\beta)^2}}$

GENERAL DIFFERENTIAL EQUATION OF MOTION: $M\ddot{x} + c\dot{x} + kx = F_{IN}$

FOR SINUSOIDAL INPUT SIGNAL: $M\ddot{x} + c\dot{x} + kx = (F_{IN})_o \sin \omega t$

GENERAL SOLUTION OF DIFFERENTIAL EQUATION: $x_G = e^{-h\omega_n t}(A \sin \omega_n t + B \cos \omega_n t)$

PARTICULAR SOLUTION OF DIFFERENTIAL EQUATION: $x_p = N_1 \sin \omega t + N_2 \cos \omega t$

SUBSTITUTING $x = x_p$ IN DIFFERENTIAL EQUATION AND SOLVING FOR N_1 AND N_2 YIELDS:

$$N_1 = \frac{(F_{IN})_o}{k}\left[(1-\beta^2)(\gamma)^2\right] \quad \text{AND} \quad N_2 = -\frac{(F_{IN})_o}{k}\left[(2h\beta)(\gamma)^2\right]$$

$$x_p = \frac{(F_{IN})_o}{k}(\gamma)^2\left[(1-\beta^2)\sin \omega t - 2h\beta \cos \omega t\right] = \frac{(F_{IN})_o}{k}(\gamma)\sin(\omega t - \phi)$$

$$x = x_G + x_p = e^{-h\omega_n t}(A \sin \omega_n t + B \cos \omega_n t) + \frac{(F_{IN})_o}{k}(\gamma)\sin(\omega t - \phi)$$

SUBSTITUTING BOUNDARY CONDITIONS $x(0) = \dot{x}(0) = 0$ INTO TOTAL SOLUTION TO THE DIFFERENTIAL EQUATION AND ITS DERIVATIVE AND SOLVING FOR A AND B YIELDS:

$$A = \frac{(F_{IN})_o}{k}(\gamma)(h \sin\phi - \beta\cos\phi) \quad \text{AND} \quad B = \frac{(F_{IN})_o}{k}(\gamma)(\sin\phi)$$

$$x = \frac{(F_{IN})_o}{k}(\gamma)\left[\sin(\omega t - \phi) + e^{-h\omega_n t}\left\{(h\sin\phi - \beta\cos\phi)\sin\omega_n t + (\sin\phi)\cos\omega_n t\right\}\right]$$

$$\frac{F_{SPRING}}{(F_{IN})_o} = \gamma\left[\sin(\omega t - \phi) + e^{-h\omega_n t}\left\{(h\sin\phi - \beta\cos\phi)\sin\omega_n t + (\sin\phi)\cos\omega_n t\right\}\right]$$

NEGLECTING THE TRANSIENT FREE-VIBRATION CONTRIBUTION, WHICH IS VERY SMALL RELATIVE TO THE STEADY-STATE CONTRIBUTION FOR THE CONDITIONS OF INTEREST, YIELDS:

$$\frac{F_{SPRING}}{(F_{IN})_o} = \gamma \sin(\omega t - \phi)$$

Fig. 98. Conventional single-degree-cf-freedom system analysis.

is shown in Fig. 99; a plot of the latter effect, generally referred to as phase shift or time lag, is shown in Fig. 100.

The natural-frequency range of the flush-mounted pressure transducer units selected is 10,000 to 23,500 cps, and the damping coefficient (h) for these units is thought to be small, say 0.10, although an exact value for this parameter is not available. Since the highest frequency component of the input signal is not likely to exceed 80 cps (see Section A.1), the critical frequency ratio for design may be taken as 0.008. The plots in Figs. 99 and 100 clearly show that for such a small amplitude ratio, both amplitude and phase distortion can be neglected, regardless of the actual value of the damping coefficient.

The natural frequency of the light-beam-oscillograph galvanometer selected is 833 cps, and the damping coefficient is 0.64. The critical frequency ratio for design is approximately 0.1. According to the plots in Figs. 99 and 100, the amplitude ratio is 1.00, and the phase shift is approximately 7.5 deg. Consequently, both amplitude and phase distortion in the galvanometer can be neglected. (A phase shift of 7.5 deg in the rise portion of a signal with a 3-msec duration corresponds to a time lag of approximately 0.25 msec, which is barely resolvable in any case--see Section 4.5.)

The single-degree-of-freedom analysis discussed above could not be used to evaluate the frequency-response characteristics of the LVDT displacement transducer selected for the WES one-dimensional compression device, since the LVDT transducer is mechanically uncoupled in its operation (see Section 3.6 and Fig. 56). The only possible time or frequency limitation associated with the LVDT is the inertia of the core system as compared

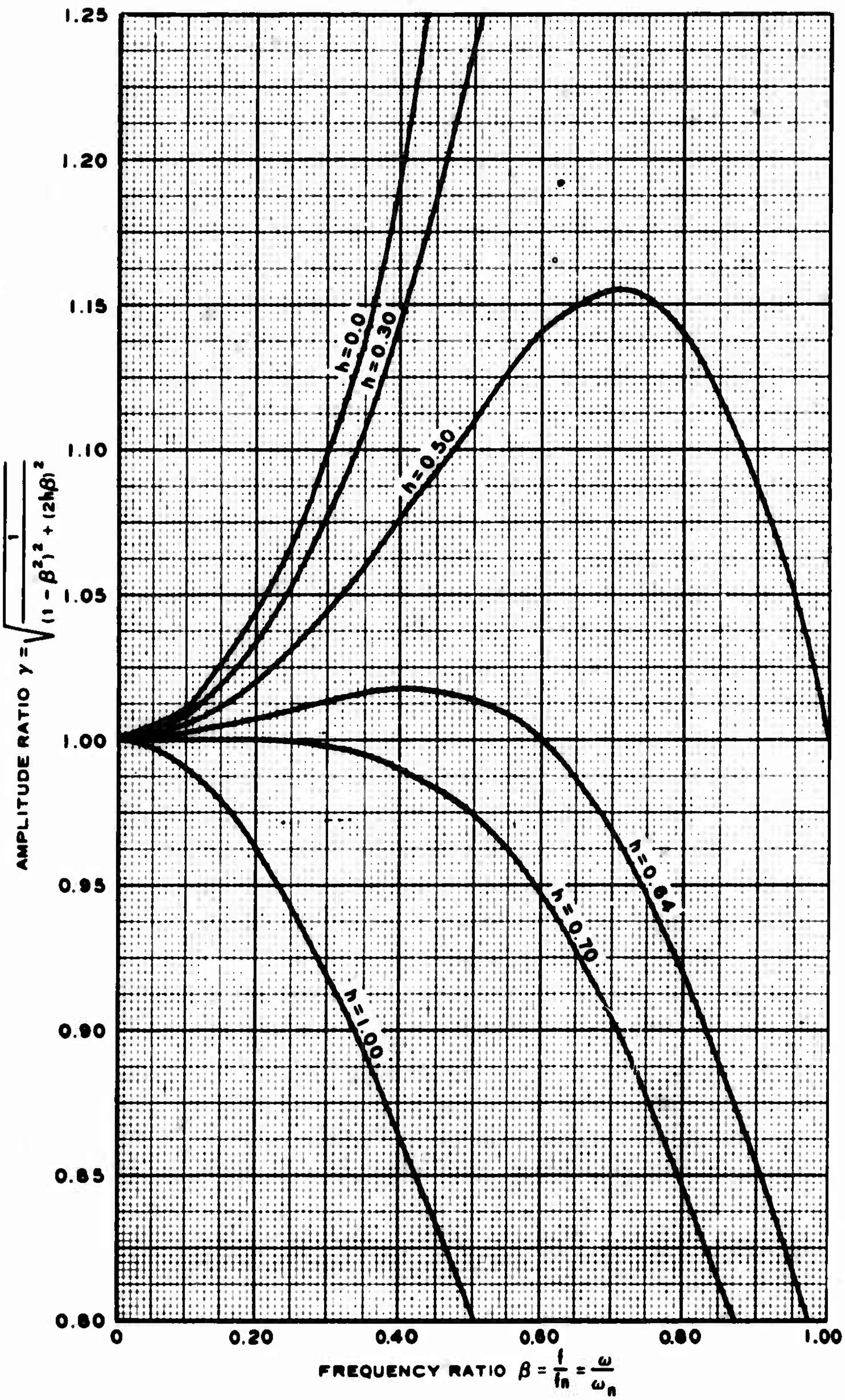


Fig. 99. Frequency-response characteristics of single-degree-of-freedom system; amplitude ratio.

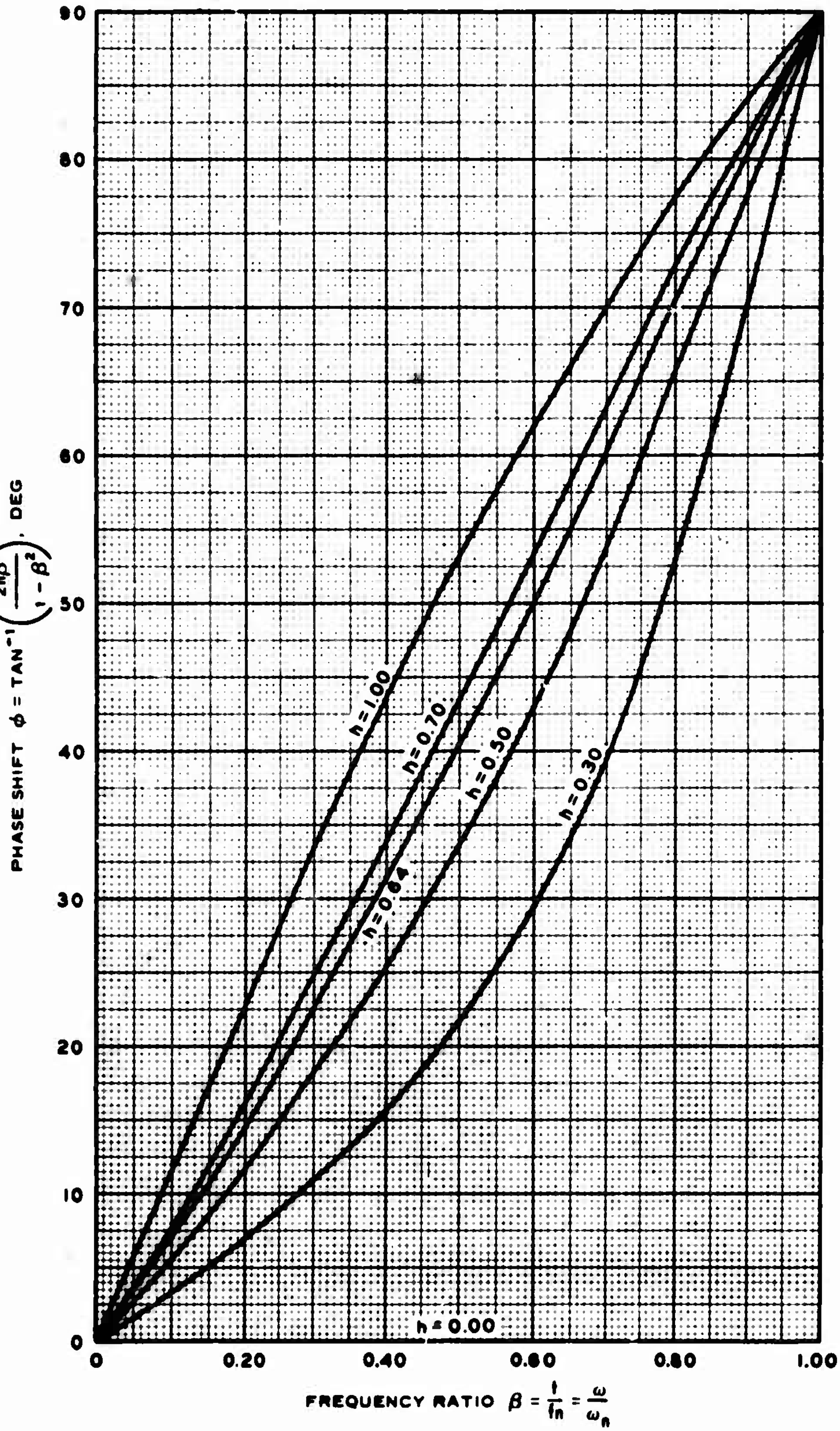


Fig. 100. Frequency-response characteristics of single-degree-of-freedom system; phase shift.

with the inertia of the specimen in its deformation. An attempt was made to evaluate this by assuming--conservatively--that the specimen and the core system are loaded completely independently and then comparing the displacement history of the core system with that of the specimen surface. The results of the analysis, which is outlined in Fig. 101, show that even when a steel core rod is used, the core system is able to follow the specimen surface throughout the loading history.

A.5 Equipment Compressibility

The amount of equipment compressibility which can be permitted without violating the design specification concerning accuracy (Section 3.1) is easily calculated. For the most severe conditions anticipated, a 1-in.-thick specimen with a constrained modulus of 200,000 psi, the deformation of the specimen surface will be 0.005 in. or 5 mils at a pressure of 1000 psi. If the contribution to experimental error resulting from equipment compressibility is to be kept to the 1-percent value specified, the deformations of all the contributing equipment components (Section 2.2) cannot be permitted to exceed 0.05 mil at a pressure of 1000 psi.

It is important to recognize the severity of such a limitation on equipment compressibility. A piece of steel only 1.5 in. thick will deform 0.05 mil under a compressive load of 1000 psi; furthermore, machining tolerances finer than 0.1 mil are beyond the capability of most precision machine shops. In view of this, it was decided to relax the equipment-compressibility limitation for certain special conditions. The 0.05-mil value was retained as a target value during design; however, deformations somewhat greater--up to 0.5 mil--were considered to be tolerable, provided

ASSUMPTIONS

ELASTIC SPECIMEN AND RIGID CORE SYSTEM

SPECIMEN AND CORE SYSTEM LOADED INDEPENDENTLY BY SAME PRESSURE-TIME PULSE

DEFINITIONS

M_c : MODULUS OF SPECIMEN

γ : UNIT WEIGHT OF SPECIMEN

L : SPECIMEN THICKNESS

x_s : MOVEMENT OF SPECIMEN SURFACE

m : MASS OF LVDT CORE SYSTEM

W : WEIGHT OF LVDT CORE SYSTEM

A : LOADED AREA OF CORE SYSTEM

x_m : MOVEMENT OF CORE SYSTEM

MOVEMENT OF LVDT CORE SYSTEM

$$F = ma = m\ddot{x}_m$$

$$\ddot{x}_m = \frac{pA}{m} = \frac{p_{max}(t/t_R)A}{m}, \text{ ASSUMING A LINEAR PRESSURE RISE}$$

$$\dot{x}_m = \int_0^t \frac{p_{max}(t/t_R)A}{m}\,dt = \frac{p_{max}At^2}{2t_Rm}$$

$$x_m = \int_0^t \frac{p_{max}At^2}{2t_Rm}\,dt = \frac{p_{max}At^3}{6t_Rm} = \frac{Apt^2}{6m}$$

MOVEMENT OF SPECIMEN SURFACE

$$x_s = \frac{pL}{M_c}$$

SOLUTION

LVDT INERTIA IS IMPORTANT FOR ALL TIMES FOR WHICH $x_s > x_m$

FOR $x_s > x_m$: $\frac{pL}{M_c} > \frac{Apt^2}{6m}$ AND $t < \left(\frac{6mL}{AM_c}\right)^{1/2}$

AS A FRACTION OF THE TOTAL LOADING TIME: $\frac{t}{t_R} < \left(\frac{6mL}{AM_ct_R^2}\right)^{1/2}$

THE FASTEST PERMISSIBLE RISE TIME IS $t_R = \frac{100\,L}{\Delta\,c} = \frac{100L}{(g)^{1/2}\Delta}\left(\frac{\gamma}{M_c}\right)^{1/2}$

FOR THE WORST CASE, THEN, LVDT INERTIA IS IMPORTANT FOR:

$$\frac{t}{t_R} < \left(\frac{6WL}{AM_cg}\right)^{1/2}\left(\frac{M_c}{\gamma}\right)^{1/2}\frac{(g)^{1/2}\Delta}{100L} = \frac{2.45\Delta}{100}\left(\frac{W/A}{\gamma L}\right)^{1/2}$$

FOR A STEEL CORE ROD: W = 0.233 LB; Δ (ACCURACY) = 1%

OTHER VALUES: A = 2.76 SQ IN., γ = 100 PCF, L = 1 IN.

$$\frac{t}{t_R} < \frac{2.45}{100}\left(\frac{12.15}{8.33}\right)^{1/2} = 3\%$$

THEREFORE, ONLY FOR THE FIRST 3 PERCENT OF THE LOADING IS THE LVDT CORE SYSTEM UNABLE TO FOLLOW THE MOVEMENT OF THE SPECIMEN SURFACE.

Fig. 101. Analysis of frequency-response characteristics of LVDT.

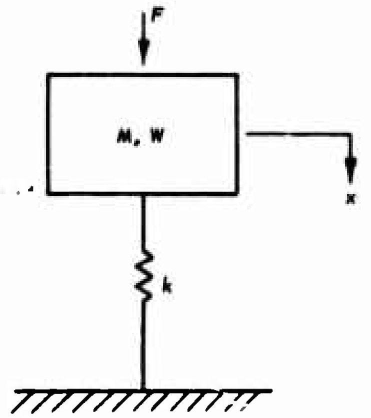
the nature of these deformations was such that they could be readily predetermined, either analytically or experimentally. Once these deformations were predetermined, they could be subtracted from the displacements measured by the LVDT transducer to provide values of the specimen-surface deformation within the accuracy specified. Since it was considered unlikely that equipment deformations in excess of 0.5 mil could be predetermined with an accuracy of ±0.05 mil--particularly for short-duration tests, during which the times at which deformations occur must be predetermined as well--deformations greater than 0.5 mil were considered to be intolerable.

A.6 Natural Period of Load-Application System

A simplified single-degree-of-freedom analysis was conducted on the load-application system of the WES one-dimensional compression device, primarily to determine if the free-vibration response of this system was causing the low-amplitude oscillations observed in the rise portion of the typical Dynapak-generated pressure pulse (see Section 4.3). The analysis is outlined in Fig. 102.

The system was taken to include the Dynapak load column, the load-column adapter, the piston assembly, the pressure fluid, and the soil specimen. The compressibility of the inevitable air in the system was neglected on the basis that the small quantity of air present would be compressed at low pressures and would not contribute significantly to the overall response of the system; the compressibility of the other components in the system was assumed to be negligible.

The natural period of the system was computed for each of the two soil containers used. The values obtained, 3.5 msec and 5.25 msec, agree



$W = Mg \approx 235$ LB FOR BOTH SOIL CONTAINERS

$(M_c)_w \approx 300{,}000$ PSI FOR WATER

$(M_c)_s \approx 30{,}000$ PSI FOR SOIL USED IN TEST PROGRAM

FOR THE MASS-SPRING SYSTEM SHOWN

$$\text{NATURAL PERIOD} = T = 2\pi\sqrt{M/k} = 2\pi\sqrt{W/gk}$$

$$\text{STIFFNESS} = k = \frac{F}{x} = \frac{pA}{\epsilon_w H_w + \epsilon_s H_s} = \frac{pA}{\frac{p}{(M_c)_w} H_w + \frac{p}{(M_c)_s} H_s} = \frac{A}{\frac{H_w}{(M_c)_w} + \frac{H_s}{(M_c)_s}}$$

FOR A 1-IN.-THICK SPECIMEN

$$k = \frac{\pi(5)^2}{\frac{2}{300{,}000} + \frac{1}{30{,}000}} = 2 \times 10^6 \text{ PSI}$$

$$T = 2\pi\sqrt{235/(386)(2 \times 10)^6} = 3.5 \times 10^{-3} \text{ SEC} = 3.5 \text{ MSEC}$$

FOR A 2.5-IN.-THICK SPECIMEN

$$k = \frac{\pi(5)^2}{\frac{2}{300{,}000} + \frac{2.5}{30{,}000}} = 0.87 \times 10^6 \text{ PSI}$$

$$T = 2\pi\sqrt{235/(386)(0.87 \times 10^6)} = 5.25 \times 10^{-3} \text{ SEC} = 5.25 \text{ MSEC}$$

Fig. 102. Analysis to determine natural frequency of load-application system.

very closely with the range of values (2 msec to 6 msec) observed during the evaluation program.

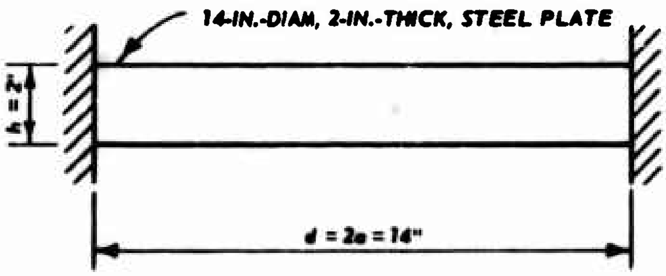
A.7 Dynamic Response Characteristics of LVDT Coil Support Plate

During a short-duration test, the entire one-dimensional compression device is subjected to a transient loading input from the Dynapak loader. The resulting transient response of the device as a whole subjects the LVDT coil support plate to a base disturbance in the form of motion (rather than force), as described in connection with the evaluation of the relative displacement between the LVDT coils and the soil container (Section 4.5). The response of the coil support plate to this base disturbance, which is transmitted to the outside periphery of the plate by the coil support colums, is important in that the resulting free vibrations in the coil support plate are erroneously reflected in the measurement of specimen-surface displacement. Ideally, the coil support plate should be infinitely rigid in bending, so that the motion of the coils at the center of the plate corresponds at all times to the motion of the fluid container in which the coils are supported.

An indication of the dynamic response characteristics of the LVDT coil support plate can be obtained by considering the plate to be a single-degree-of-freedom system reflecting the lowest mode of vibration of the clamped plate in bending (Fig. 103). The results must be considered to be approximate only because the fairly large holes in the plate, which affect both the mass of the plate and its stiffness in bending, are neglected in the analysis, and because the plate is not truly clamped at its support. It should be noted, however, that the holes in the plate reduce both the

inertia and the stiffness, so that these effects tend to compensate each other. Also, although the fixed-support assumption is not conservative, the plate clearly is not simply supported either; furthermore, the nonconservative assumption is somewhat offset by the conservative assumption of an 80-cps sinusoidal base-motion disturbance (Section A.1).

The results of the analysis in Fig. 103 show that the LVDT coil support plate is effectively rigid in bending, as desired, since the frequency ratio between the fastest anticipated input and the free-vibration response of the plate is only 0.02. It is also shown that, even for accelerations of the coil support plate as large as 3 g's (observed only once in the entire evaluation program), the difference in motion (u_{max}) between the LVDT coils at the center of the coil support plate and the fluid container does not approach the maximum permissible value of 0.05 mil (Section A.5). (The equation used to show this in Fig. 103 was taken from Fig. 71, where the well-known solution to the sinusoidal base-disturbance problem is outlined.)



$E = 30 \times 10^6$ PSI

$\nu = 0.3$

$$D = \frac{Eh^3}{12(1-\nu^2)} = 22 \times 10^6 \text{ PSI-IN.}^3$$

$\gamma = 0.286$ LB/IN.^{3}

a. SYSTEM ANALYZED

$$f_n = \frac{10.2}{2\pi}\sqrt{\frac{gD}{\gamma h}} \qquad \text{(TIMOSHENKO, 1955)}$$

$$f_n = \frac{10.2}{2\pi}\sqrt{\frac{(386)\,(22 \times 10^6)}{(0.286)\,(2)}}$$

$$f_n = 3750 \text{ CPS}$$

$$\frac{f}{f_n} = \frac{80}{3750} \approx 0.02$$

b. CALCULATION OF NATURAL FREQUENCY (FIRST MODE)

IF x = VERTICAL DISPLACEMENT OF CENTER OF PLATE, y = VERTICAL DISPLACEMENT OF SUPPORT, & $u = x - y$, THEN FOR $y = y_{max} \sin \omega t$ AND $\frac{f}{f_n} = 0.02$:

$$u_{max} = \frac{\omega^2 y_{max}}{\omega_n^2} = \frac{\ddot{y}_{max}}{(2\pi f_n)^2} = \frac{(3 \times 386)}{(4\pi^2)(3750)^2} = 2 \times 10^{-6} \text{ IN.}$$

$$u_{max} = 0.002 \text{ MILS}$$

c. CALCULATION OF MAXIMUM ERROR IN DISPLACEMENT MEASUREMENT

Fig. 103. Single-degree-of-freedom analysis of LVDT coil support plate.

APPENDIX B

TEST RESULTS

B.1 Key Equipment-Compressibility Tests

The most extensive single experimental effort in the evaluation of the WES, general-purpose, one-dimensional compression test facility was the equipment-compressibility study, a series of 71 tests conducted to identify and eliminate the various sources of equipment compressibility which had been overlooked in the original design of the device and its appurtenances (Sections 3.5 and 3.6). Elimination of the various sources of equipment compressibility resulted in several modifications to the one-dimensional compression device, most of which were associated with the mechanical load-support system (Section 4.4). Also affected were the load-application system (Section 4.3) and the measurement system (Section 4.5). The test data required to support the various pertinent discussions are presented herein for convenience in reference.

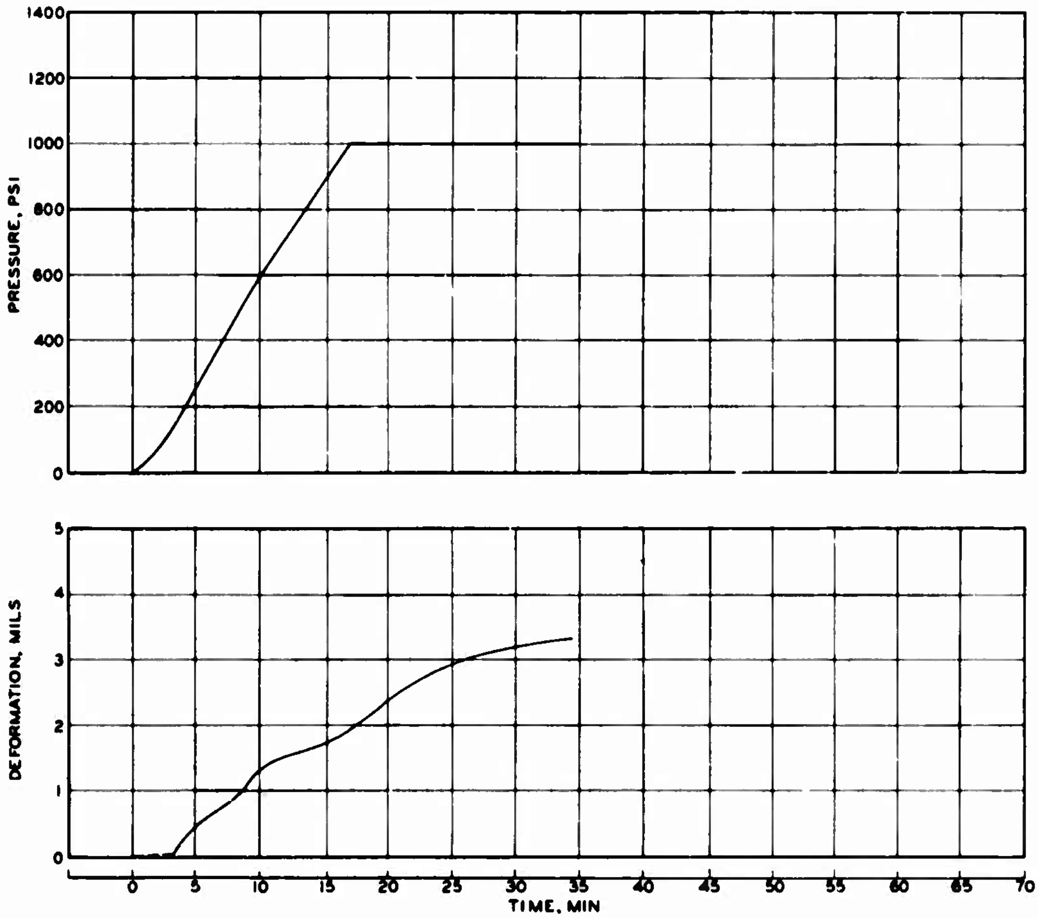
The key equipment compressibility-tests in the series were Test Nos. 4, 15, 16, 17, 22, 23, 25, 28, 30, 47, 51, 56, 66, 70, and 71. The data for these tests are presented in numerical order by test number in Figs. 104 through 118.

B.2 Preliminary Testing Program

The comprehensive experimental program which was undertaken to evaluate the general-purpose, one-dimensional compression test facility developed at WES was concluded by conducting a few actual tests with the device assembled in each of the two test configurations (Section 3.2). The purpose of the tests was to provide some indication of the performance

of the dynamic loading machine (Section 4.3) and that of the device as a whole (Section 4.6), although some information was also obtained about the performance of individual elements within the device (Sections 4.3 through 4.5). The test program is outlined in Section 4.1, and the data obtained are presented herein for convenience in reference.

The data for Test Nos. A01A01 through A01A05, all original-type tests conducted with the equipment assembled in the auxiliary configuration, are presented in Figs. 119 through 124; Test No. A01A04 consisted of two parts, and the data for this test are presented in two figures, Figs. 122 and 123. The data for Test Nos. A01P01 through A01P04, all original-type tests conducted with the equipment assembled in the principal configuration, are presented in Figs. 125 through 128. The data for Test Nos. A01R01, A01R02, and A01R03, all repeat or check tests, are presented in Figs. 129, 130, and 131, respectively.



TEST INFORMATION

TEST NO.: 4
I D NO.: 001116
SOIL TYPE: NONE
RELATIVE DENSITY: NA
SATURATION: NA
SPECIMEN THICKNESS: 0.0 INCHES
CONFIGURATION: AUXILIARY (ORIGINAL)

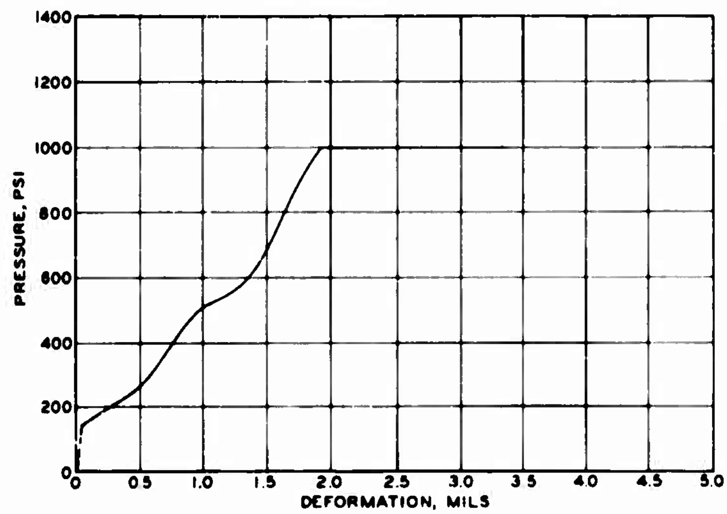
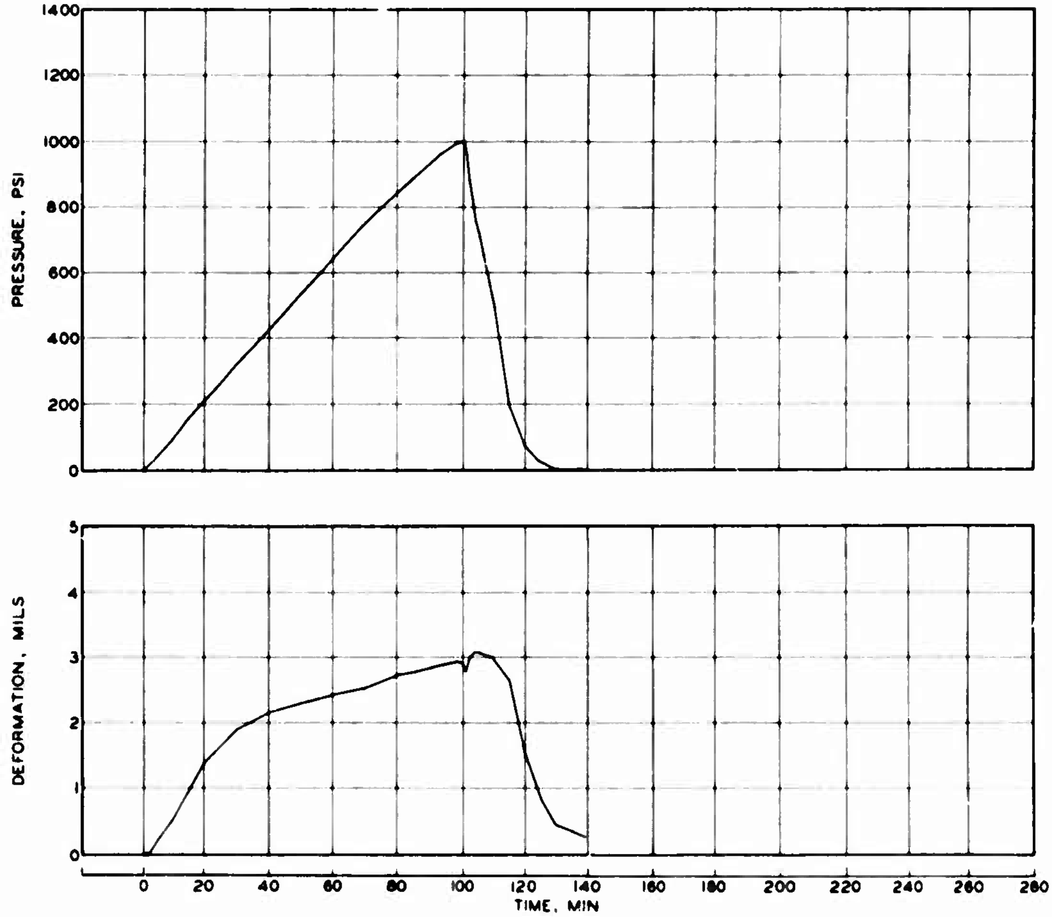


Fig. 104. Results of Test No. 4 in equipment-compressibility study.



TEST INFORMATION

TEST NO: 15
ID NO.: 003246
SOIL TYPE: NONE
RELATIVE DENSITY: NA
SATURATION: NA
SPECIMEN THICKNESS: 0.0 INCHES
CONFIGURATION: AUXILIARY (ORIGINAL)

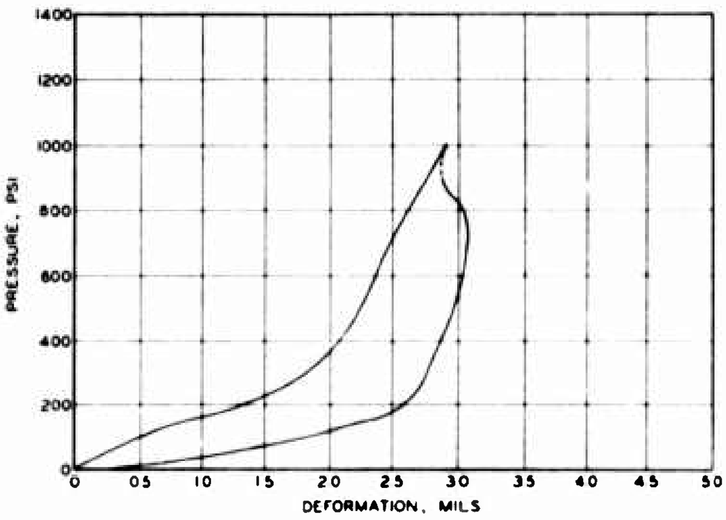
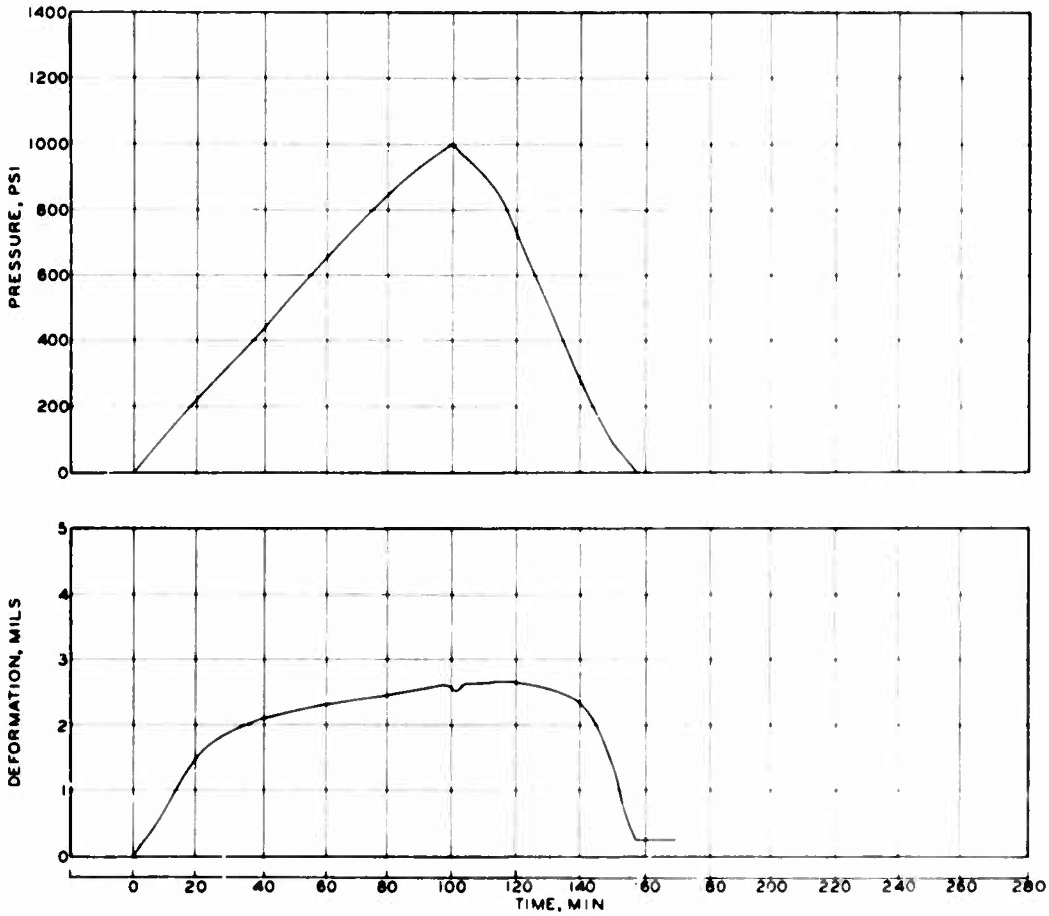
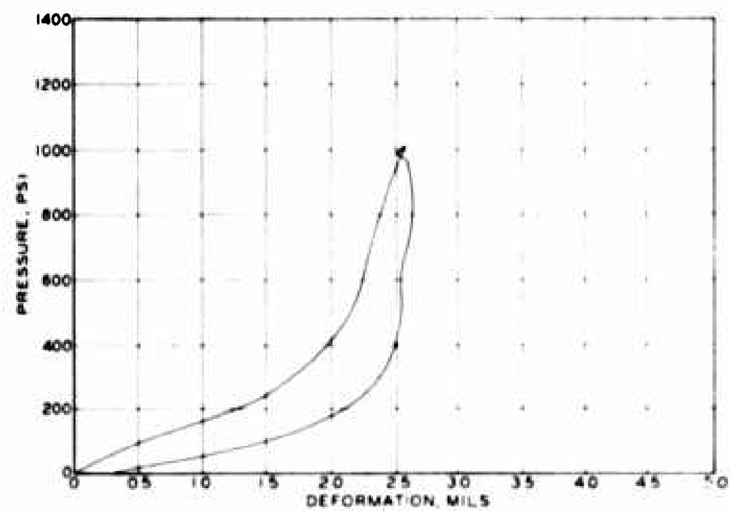


Fig. 105. Results of Test No. 15 in equipment-compressibility study.

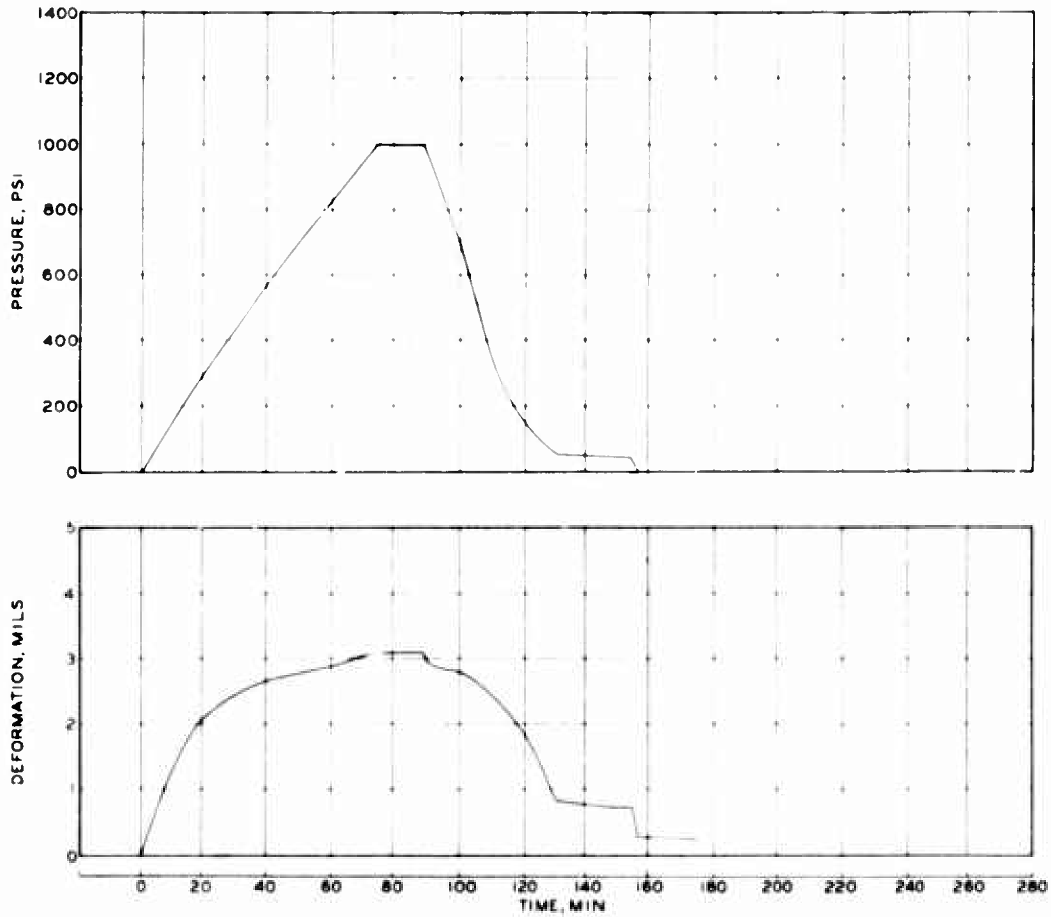




TEST INFORMATION

TEST NO 16
I D NO 003256
SOIL TYPE NONE
RELATIVE DENSITY NA
SATURATION:NA
SPECIMEN THICKNESS 0.0 INCHES
CONFIGURATION AUXILIARY (ORIGINAL)

Fig. 106. Results of Test No. 16 in equipment-compressibility study.



TEST INFORMATION

TEST NO 17
I D NO 003288
SOIL TYPE NONE
RELATIVE DENSITY NA
SATURATION NA
SPECIMEN THICKNESS 0.0 INCHES
CONFIGURATION AUXILIARY (ORIGINAL)

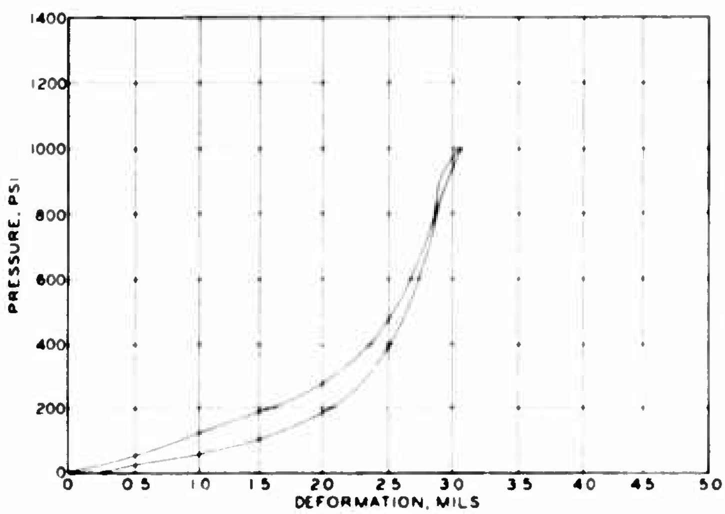
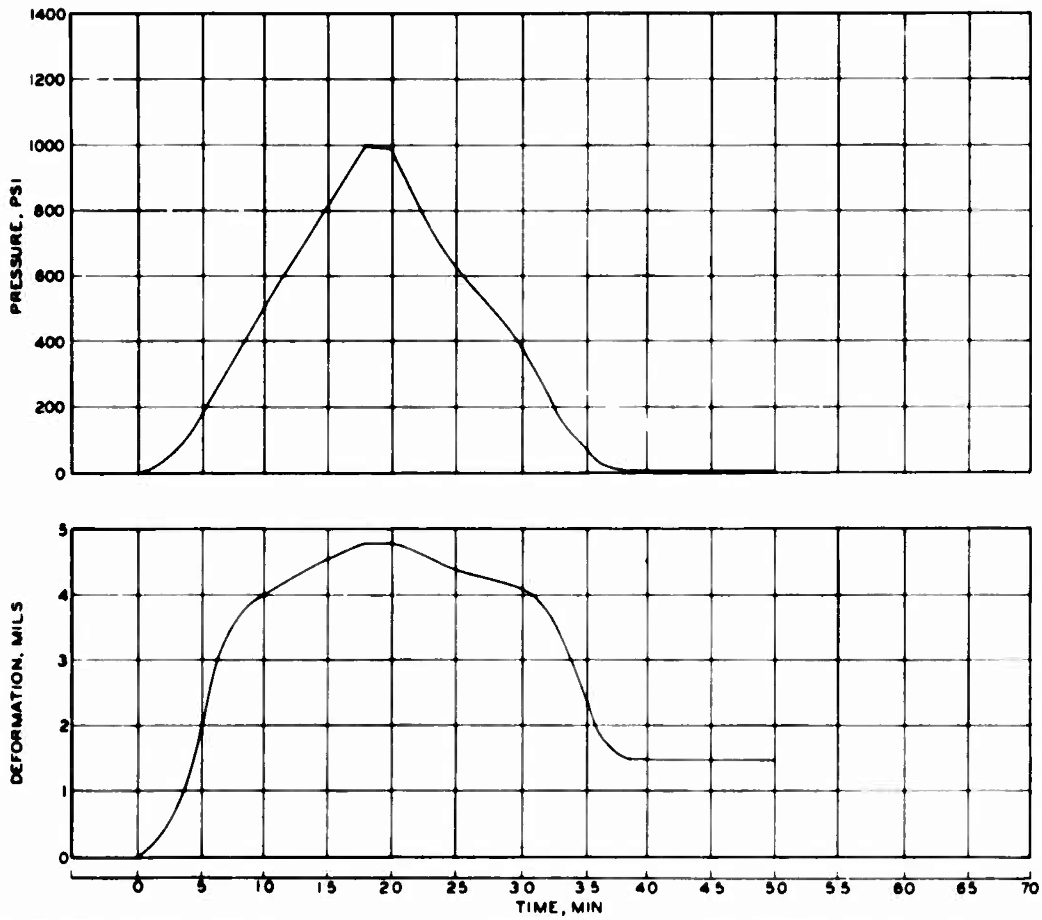


Fig. 107. Results of Test No. 17 in equipment-compressibility study.



TEST INFORMATION

TEST NO: 22
I D NO 004276
SOIL TYPE: NONE
RELATIVE DENSITY: NA
SATURATION: NA
SPECIMEN THICKNESS 0.0 INCHES
CONFIGURATION AUXILIARY (ORIGINAL)

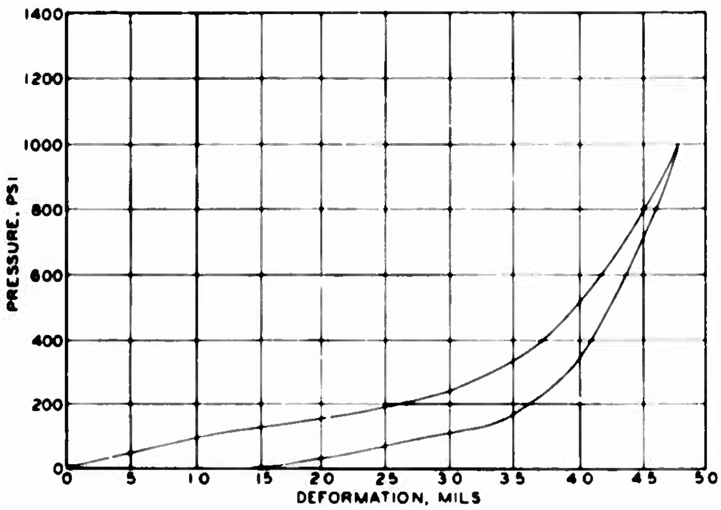
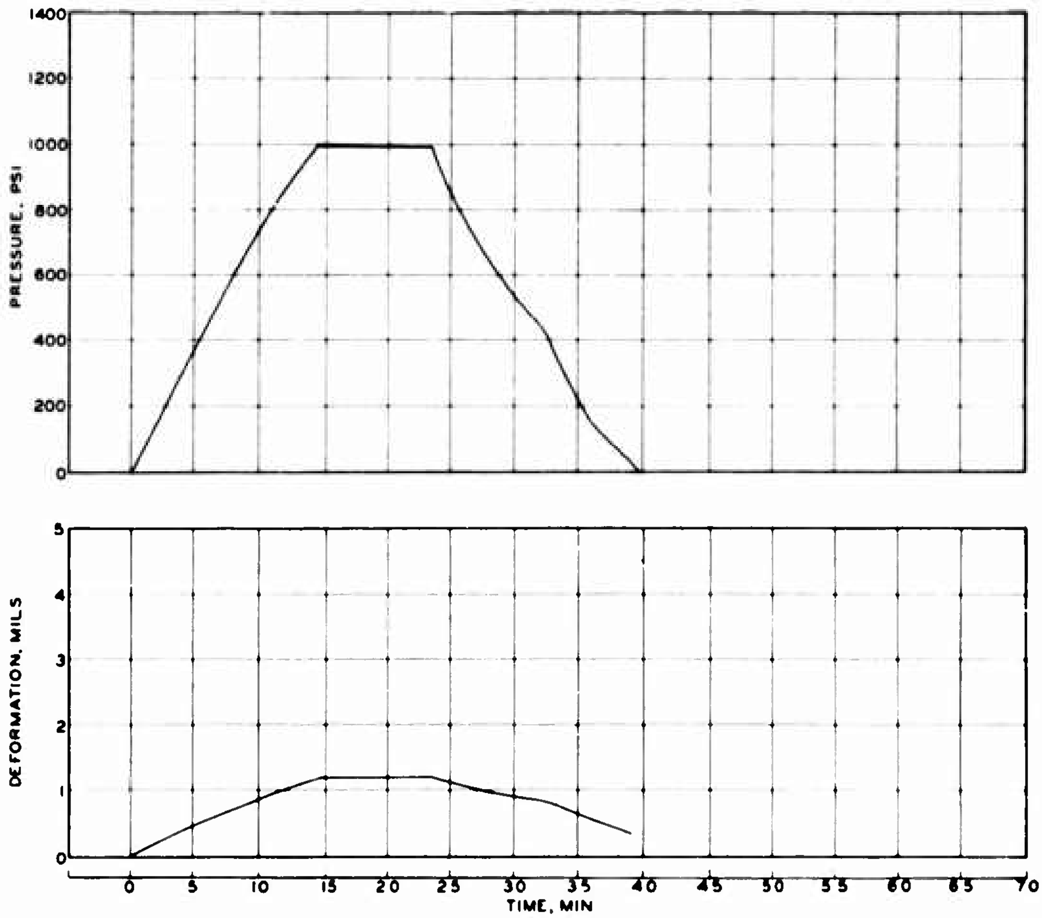


Fig. 108. Results of Test No. 22 in equipment-compressibility study.



TEST INFORMATION

TEST NO 23
I D NO 005026
SOIL TYPE NONE
RELATIVE DENSITY NA
SATURATION NA
SPECIMEN THICKNESS 0.0 INCHES
CONFIGURATION AUXILIARY (ORIGINAL)

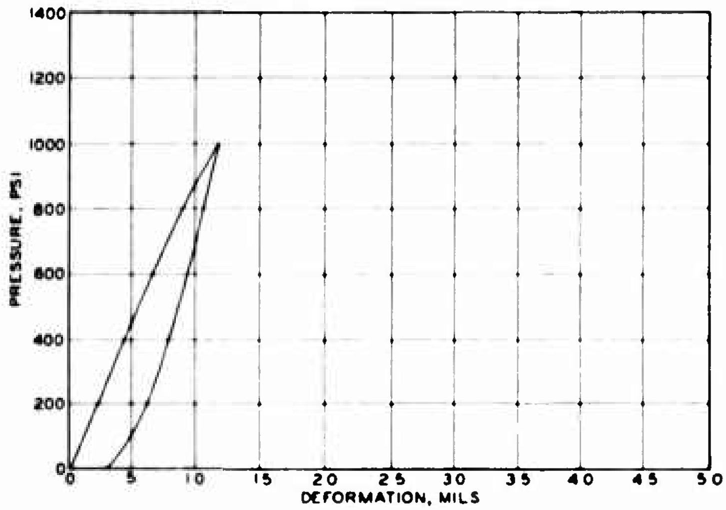


Fig. 109. Results of Test No. 23 in equipment-compressibility study.

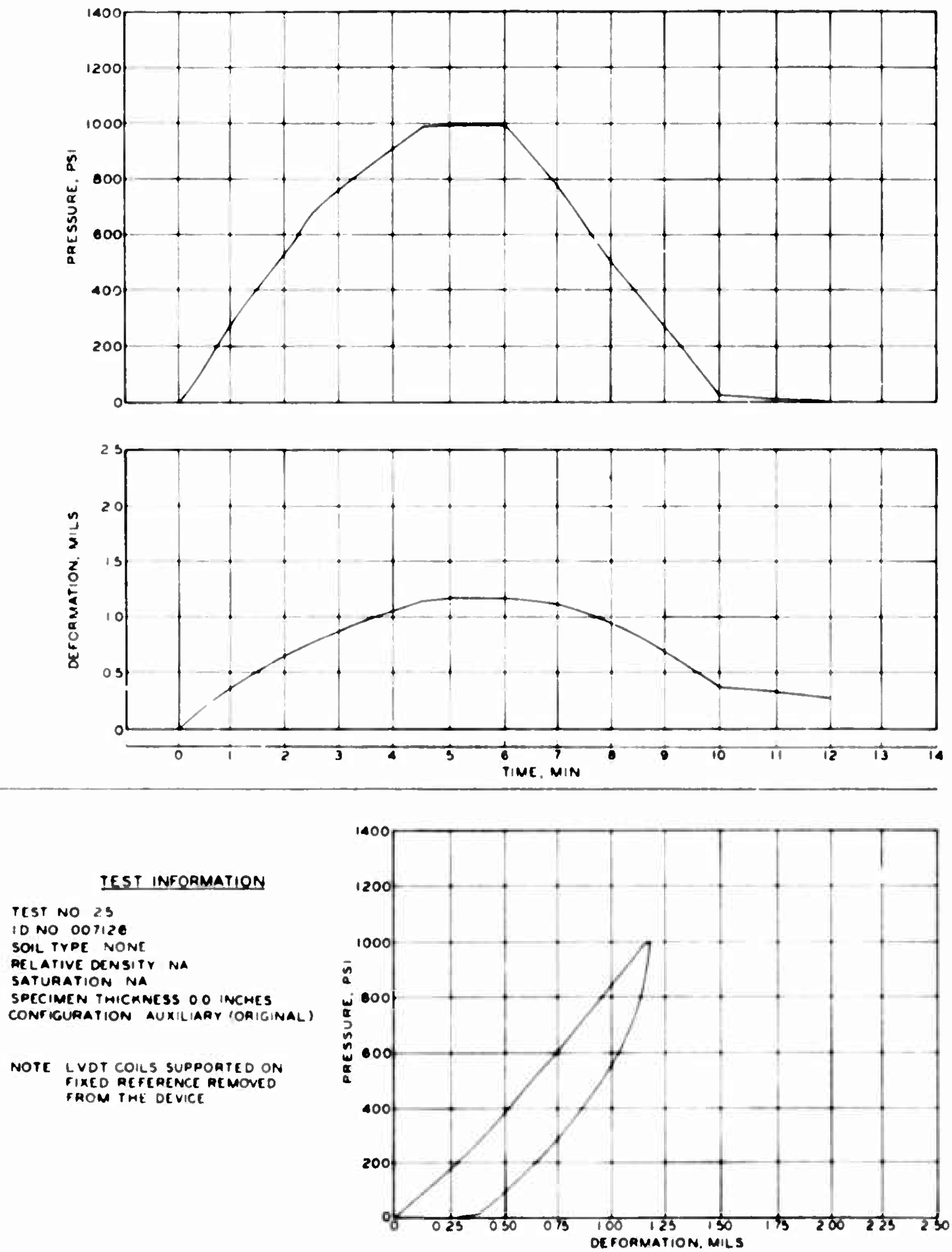
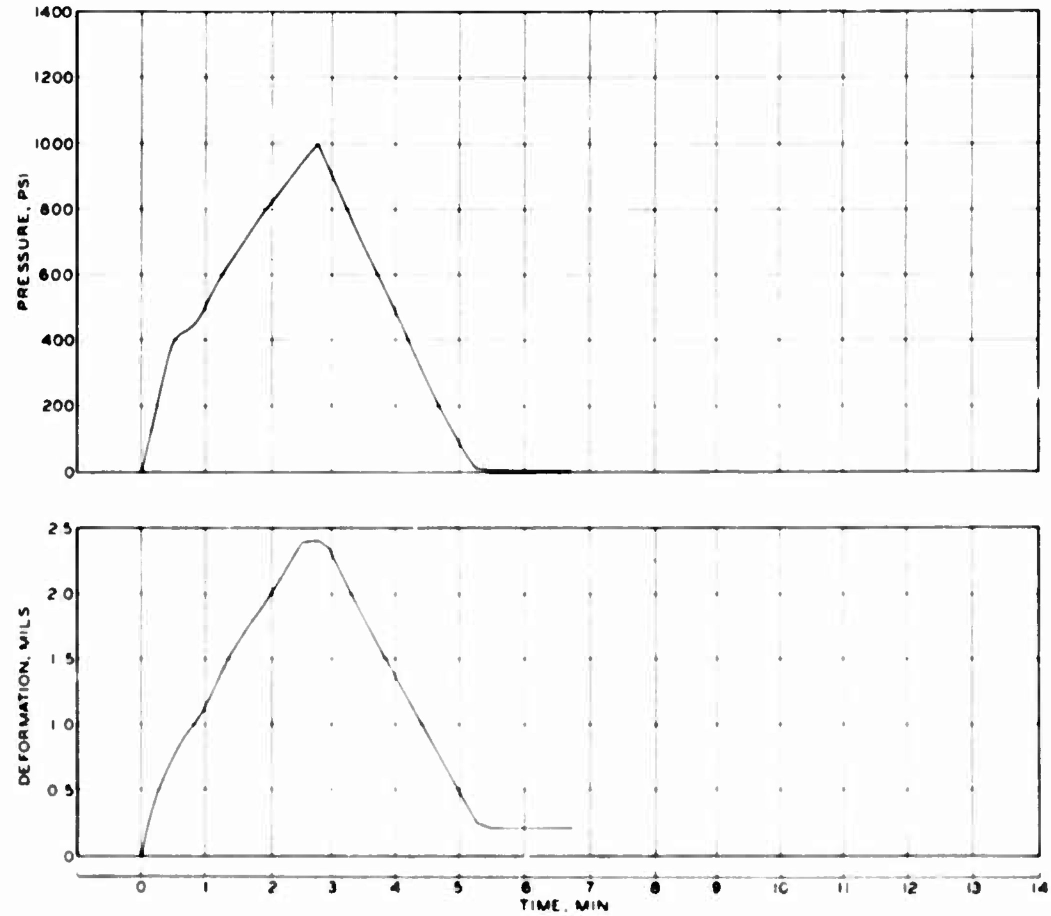


Fig. 110. Results of Test No. 25 in equipment-compressibility study.



TEST INFORMATION

TEST NO 28
I D NO 007146
SOIL TYPE NONE
RELATIVE DENSITY NA
SATURATION NA
SPECIMEN THICKNESS 00 INCHES
CONFIGURATION AUXILIARY (ORIGINAL)

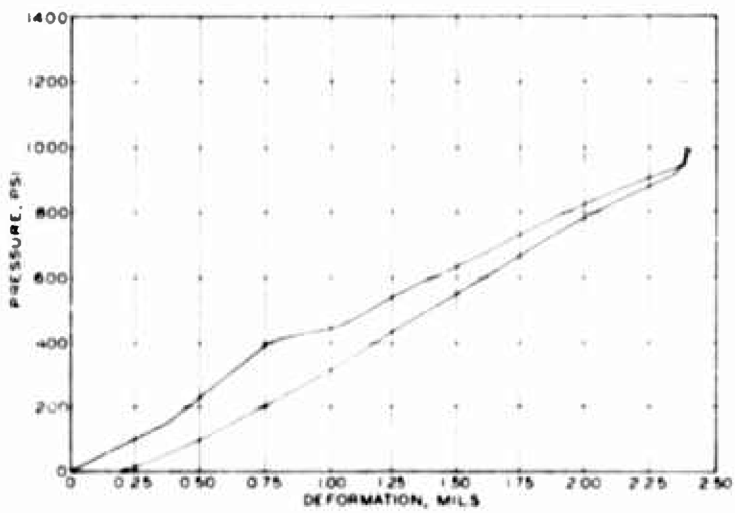
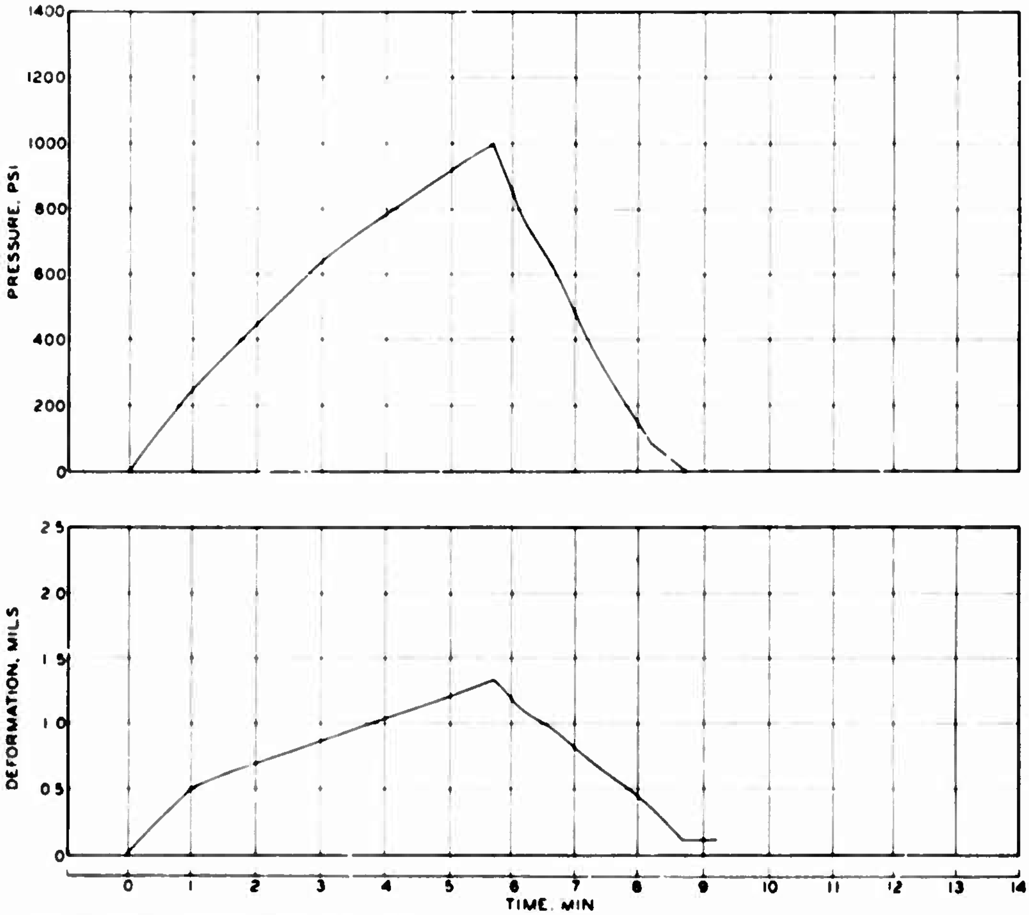


Fig. 111. Results of Test No. 28 in equipment-compressibility study.



TEST INFORMATION

TEST NO 30
I D NO 007216
SOIL TYPE NONE
RELATIVE DENSITY NA
SATURATION NA
SPECIMEN THICKNESS 0.0 INCHES
CONFIGURATION AUXILIARY (ORIGINAL)

NOTE HIGH INITIAL TORQUE ON
ASSEMBLY BOLTS

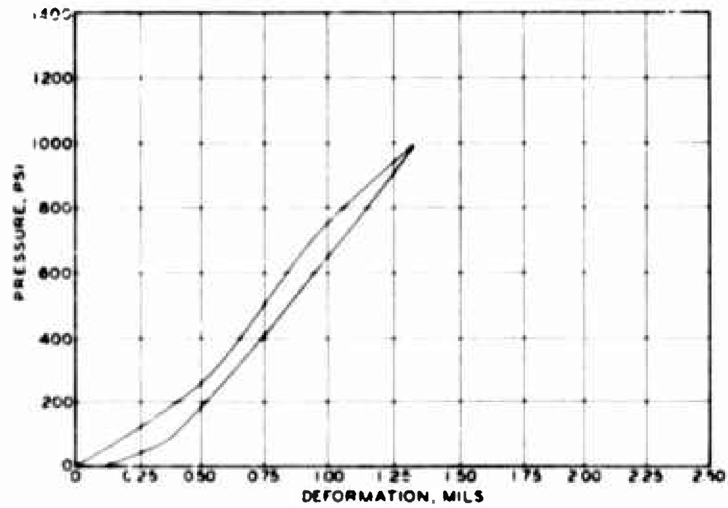
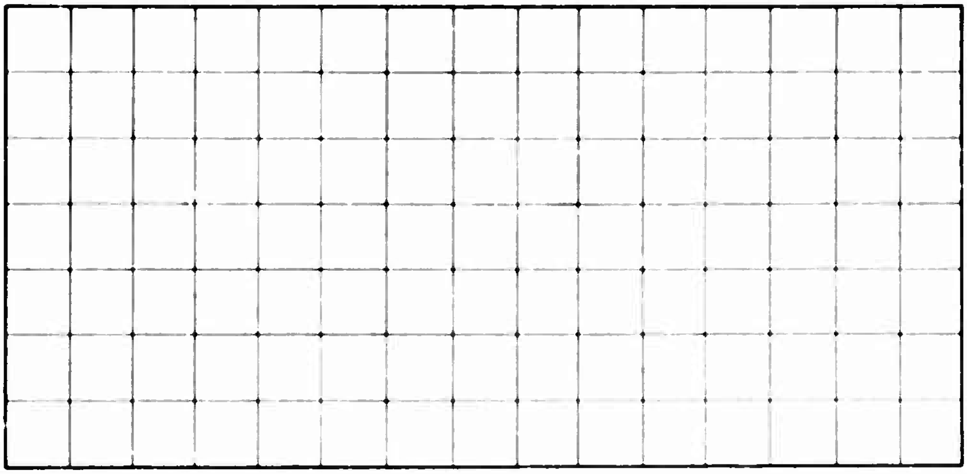
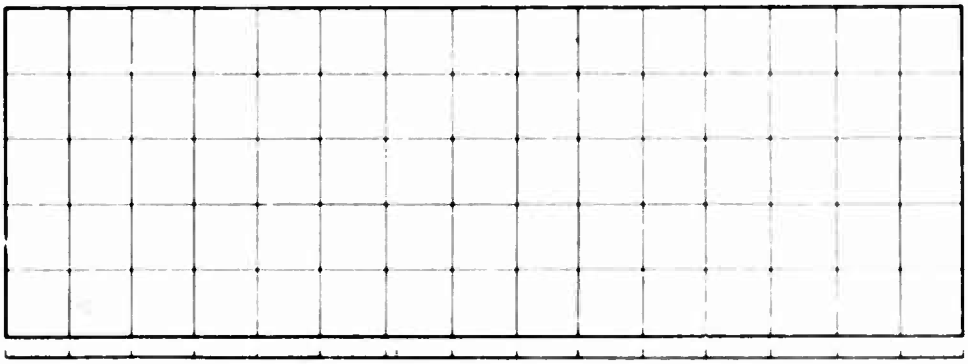


Fig. 112. Results of Test No. 30 in equipment-compressibility study.





TEST INFORMATION

TEST NO: 47
I D NO: 006276
SOIL TYPE: NONE
RELATIVE DENSITY: NA
SATURATION: NA
SPECIMEN THICKNESS: 0.0 INCHES
CONFIGURATION: PRINCIPAL (ORIGINAL)

NOTE: PRESSURE WAS APPLIED IN INCREMENTS, AND EACH INCREMENT WAS HELD FOR SEVERAL MINUTES.

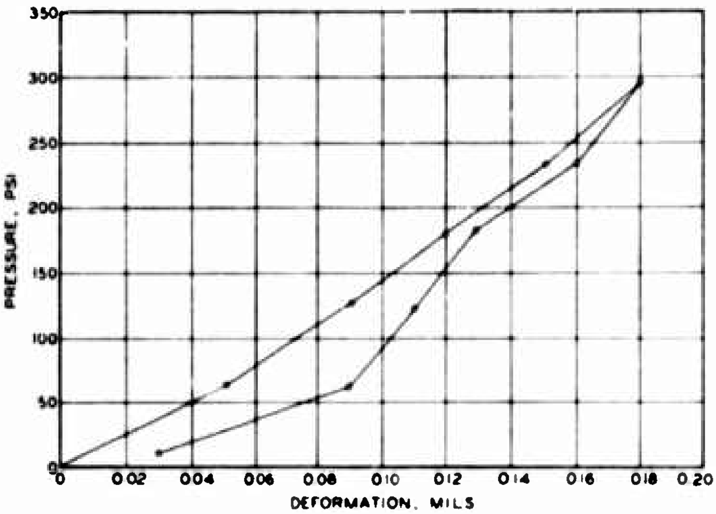


Fig. 113. Results of Test No. 47 in equipment-compressibility study.

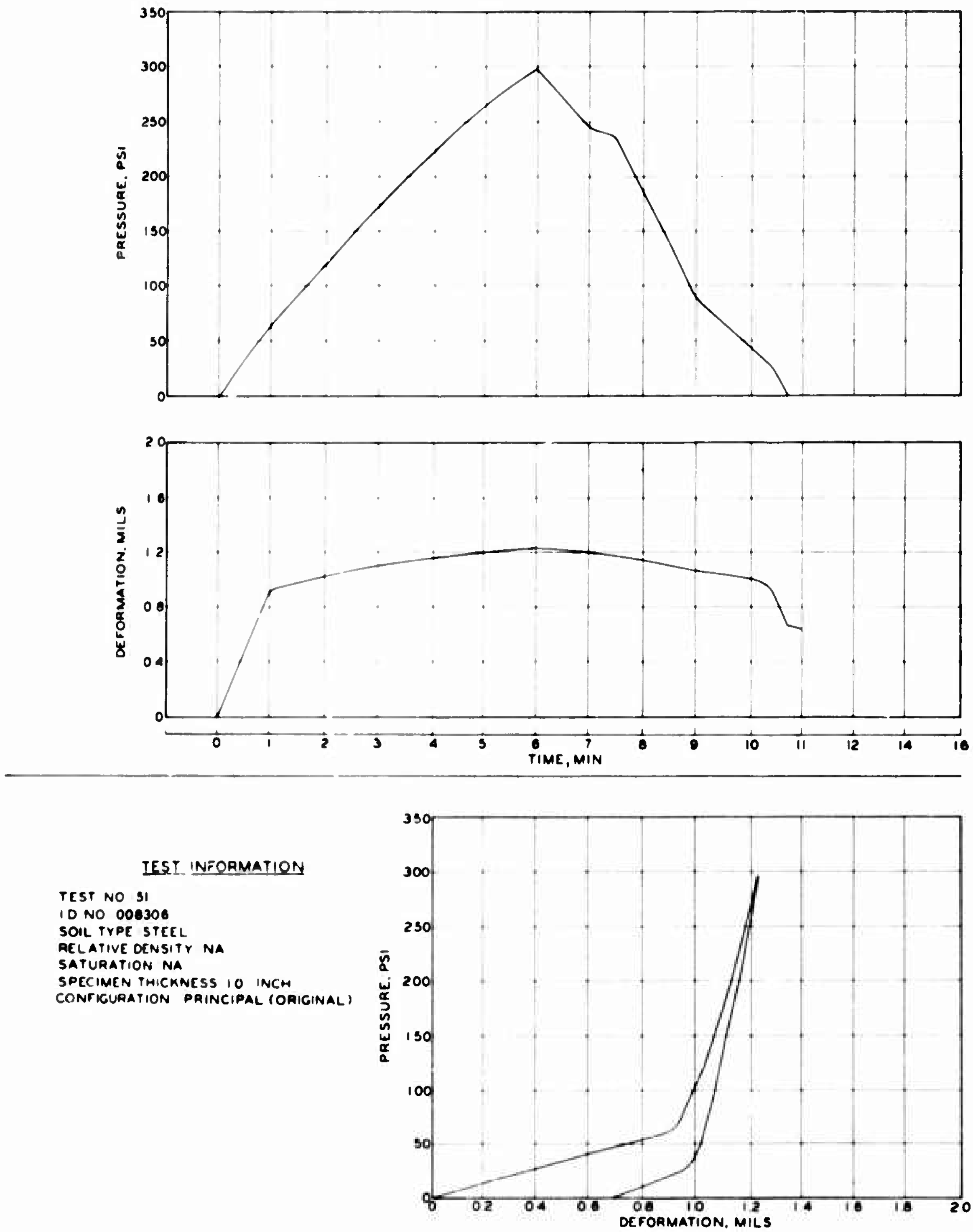
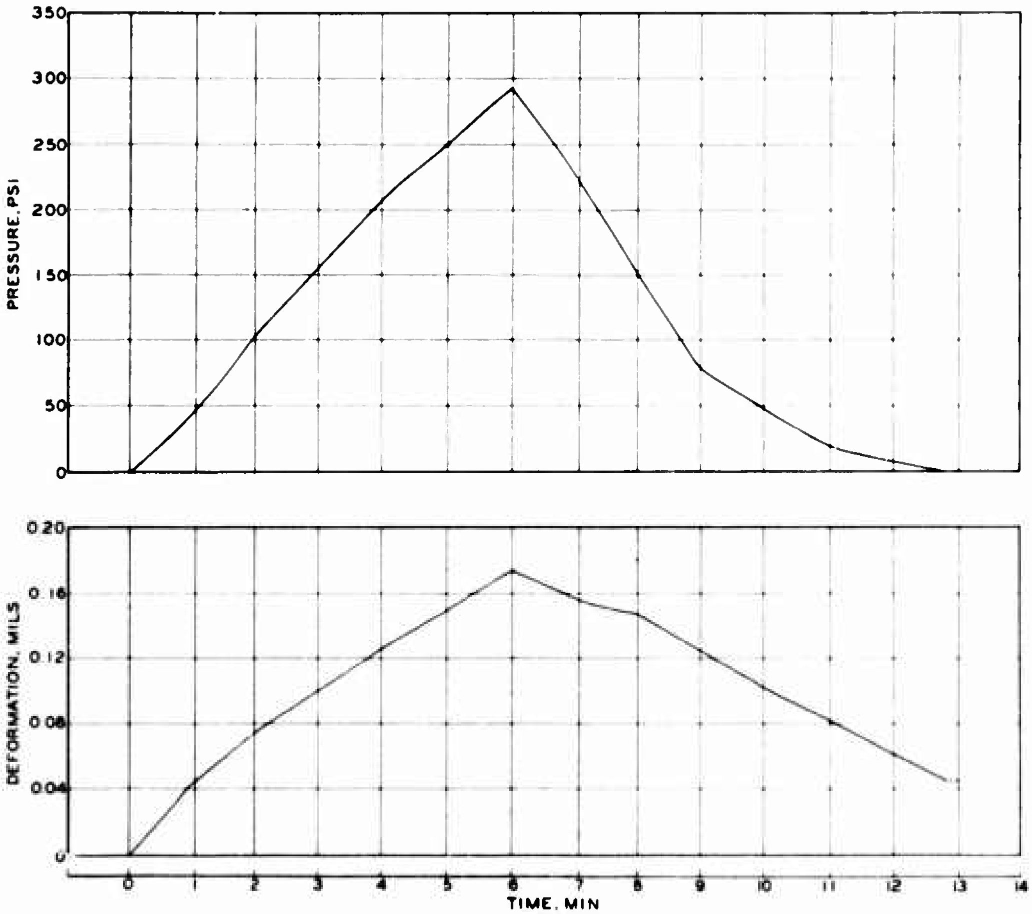


Fig. 114. Results of Test No. 51 in equipment-compressibility study.



TEST INFORMATION

TEST NO : 56
I D NO. : 009086
SOIL TYPE : STEEL
RELATIVE DENSITY : NA
SATURATION : NA
SPECIMEN THICKNESS : 1.0 INCH
CONFIGURATION : PRINCIPAL (ORIGINAL)

NOTE : SOIL CONTAINER FILLED WITH WATER BEFORE PLACEMENT OF SPECIMEN.

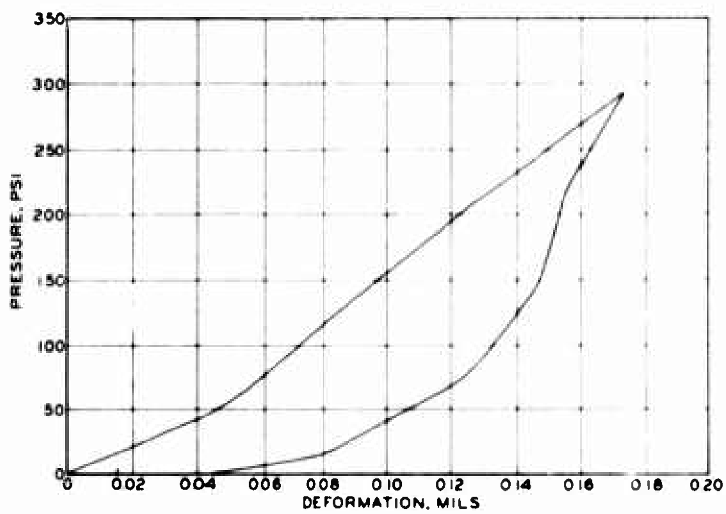
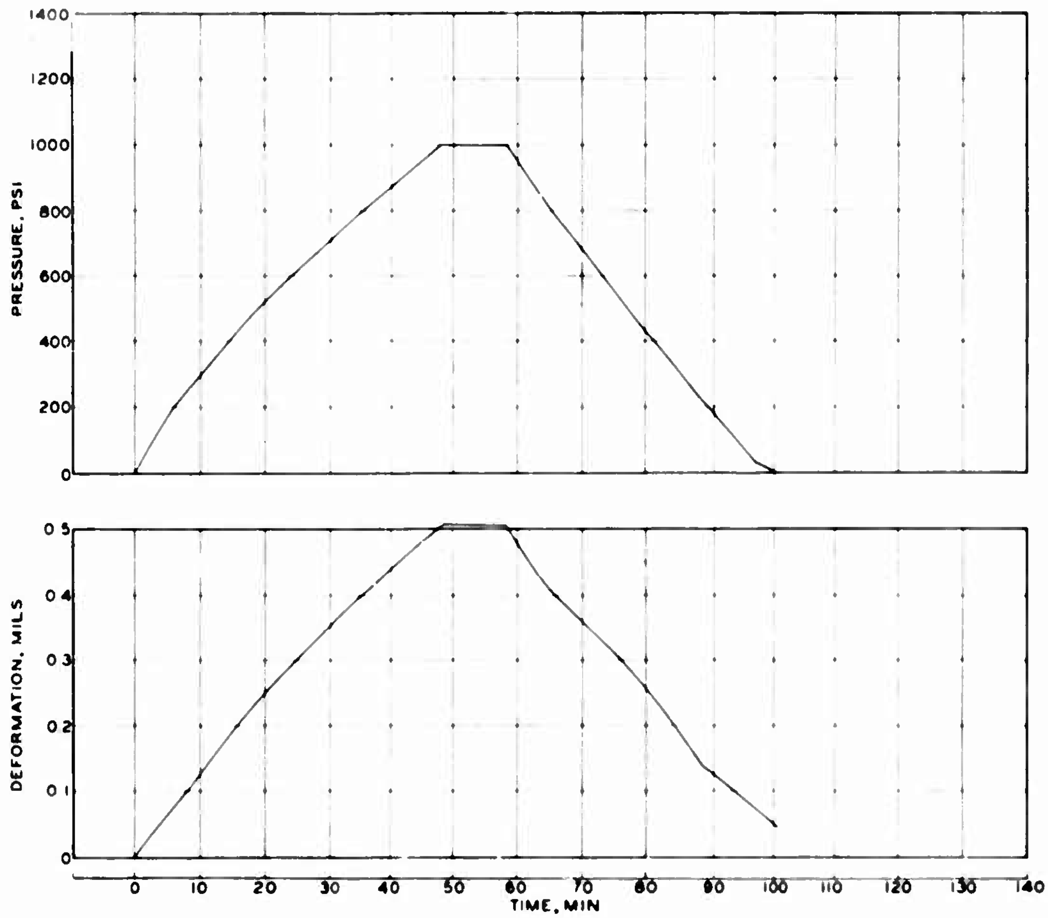


Fig. 115. Results of Test No. 56 in equipment-compressibility study.



TEST INFORMATION

TEST NO 66
I D NO 010116
SOIL TYPE NONE
RELATIVE DENSITY NA
SATURATION NA
SPECIMEN THICKNESS 0.0 INCHES
CONFIGURATION AUXILIARY (MODIFIED)

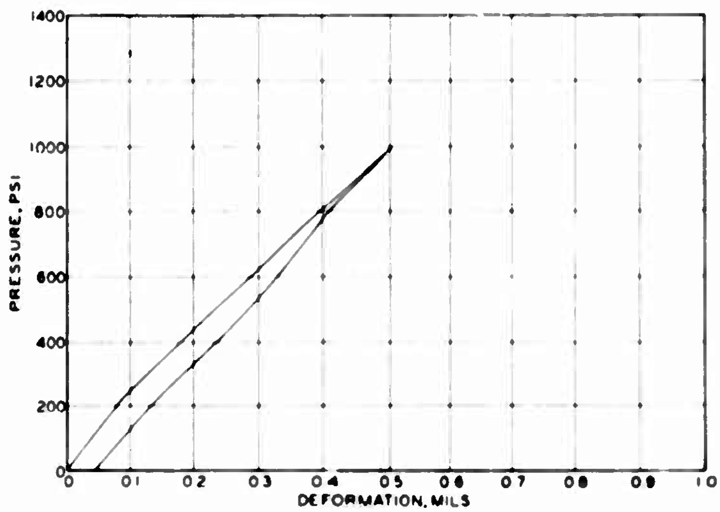
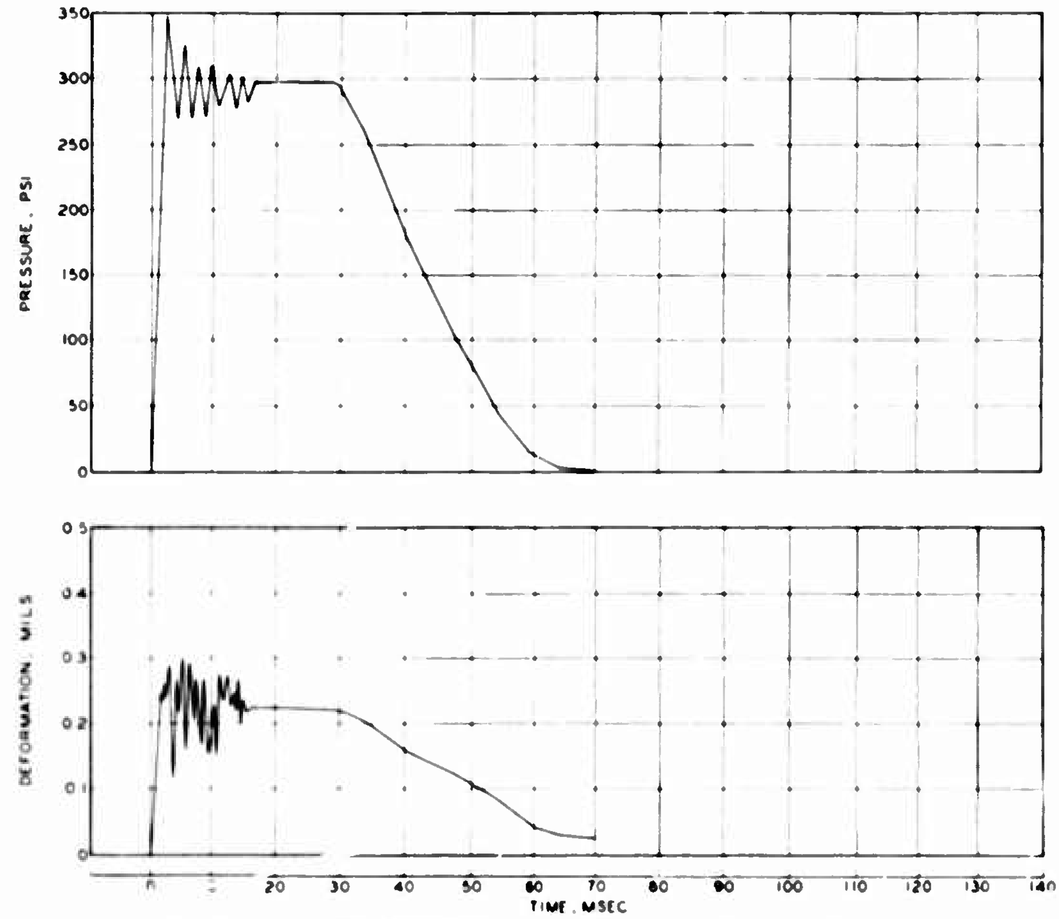


Fig. 116. Results of Test No. 66 in equipment-compressibility study.



TEST INFORMATION

TEST NO 70
I D NO 006227
SOIL TYPE NONE
RELATIVE DENSITY NA
SATURATION NA
SPECIMEN THICKNESS 0.0 INCHES
CONFIGURATION PRINCIPAL (MODIFIED)

NOTE EFFECTIVE RISE TIME FASTER THAN INTENDED

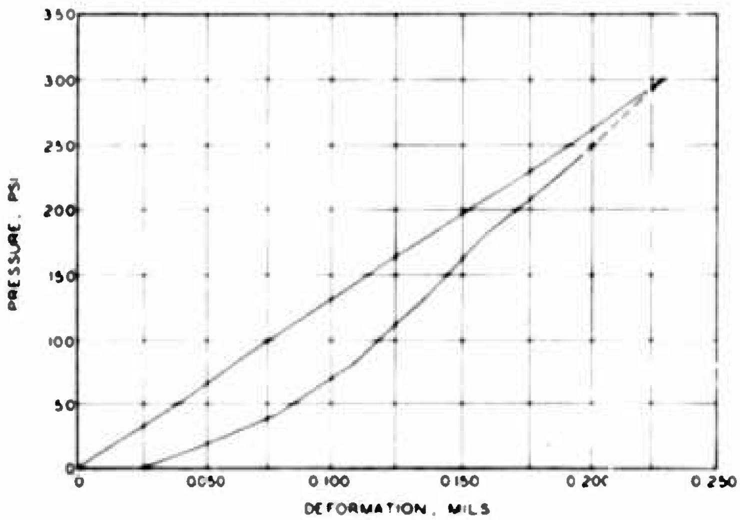
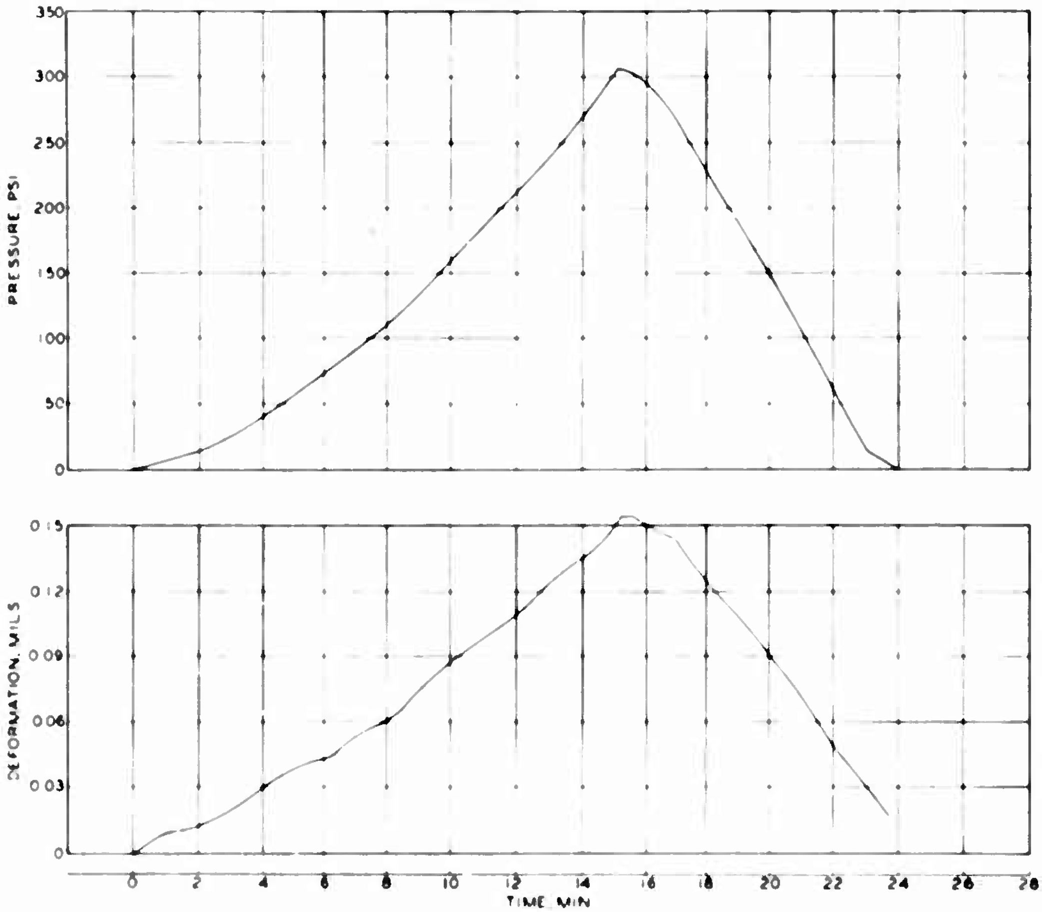


Fig. 117. Results of Test No. 70 in equipment-compressibility study.



TEST INFORMATION

TEST NO 71
ID NO 006237
SOIL TYPE NONE
RELATIVE DENSITY NA
SATURATION NA
SPECIMEN THICKNESS 0.0 INCHES
CONFIGURATION PRINCIPAL (MODIFIED)

NOTE LOAD GENERATOR WAS DYNAPAK

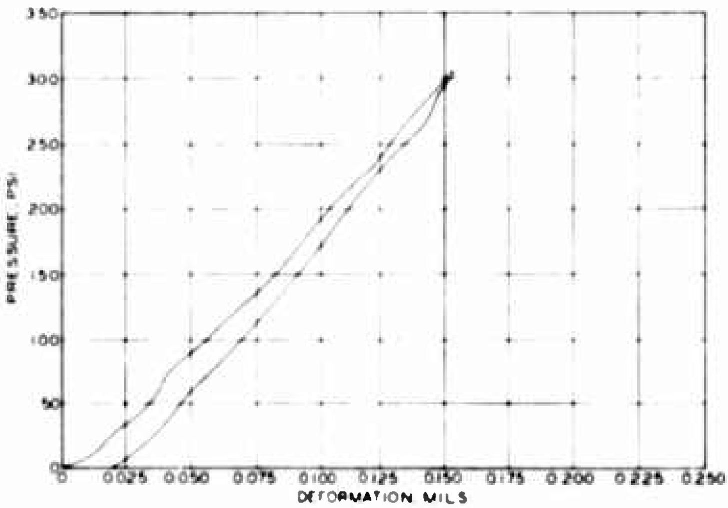
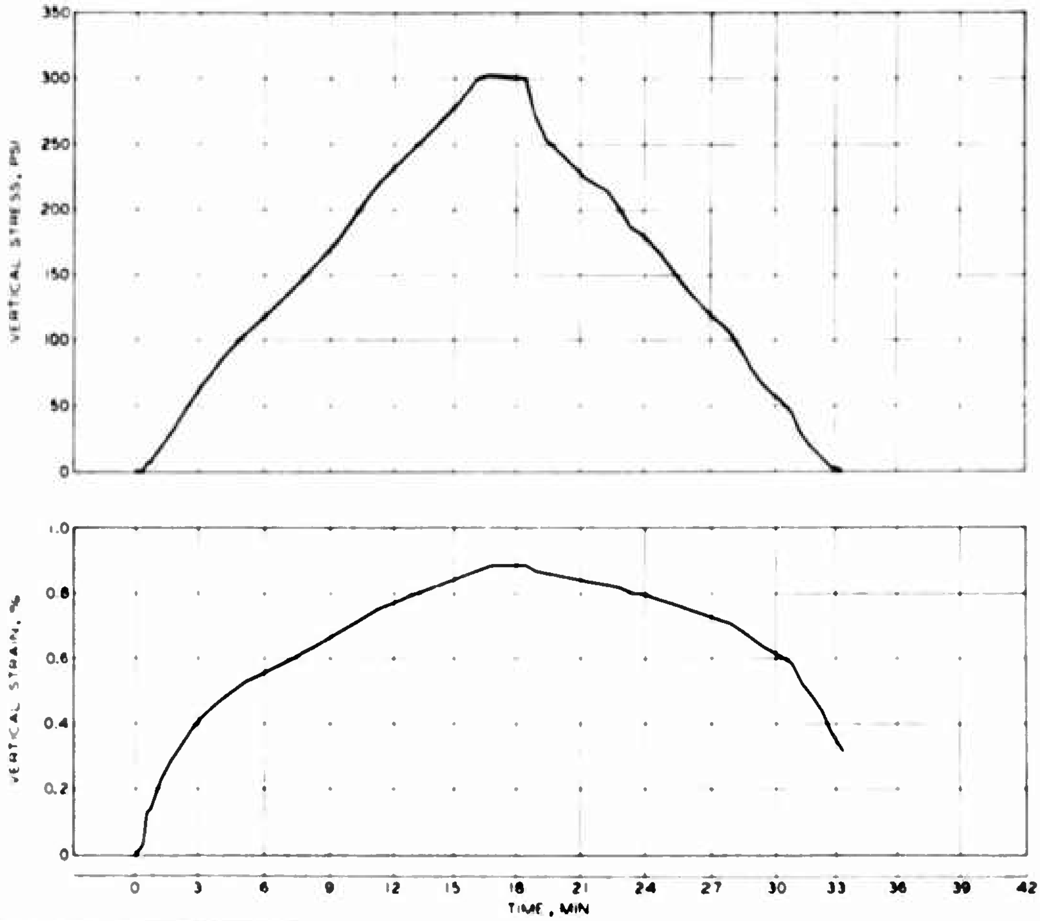


Fig. 118. Results of Test No. 71 in equipment-compressibility study.



TEST INFORMATION

TEST NO A01A01
I D NO 112026
SOIL TYPE REID-BEDFORD MODEL SAND
RELATIVE DENSITY 93.2 PERCENT
SATURATION 0.0 PERCENT
SPECIMEN THICKNESS 1.0 INCHES
CONFIGURATION AUXILIARY

NOTE BASIC LONG-DURATION TEST WITH 1-IN SOIL SPECIMEN.

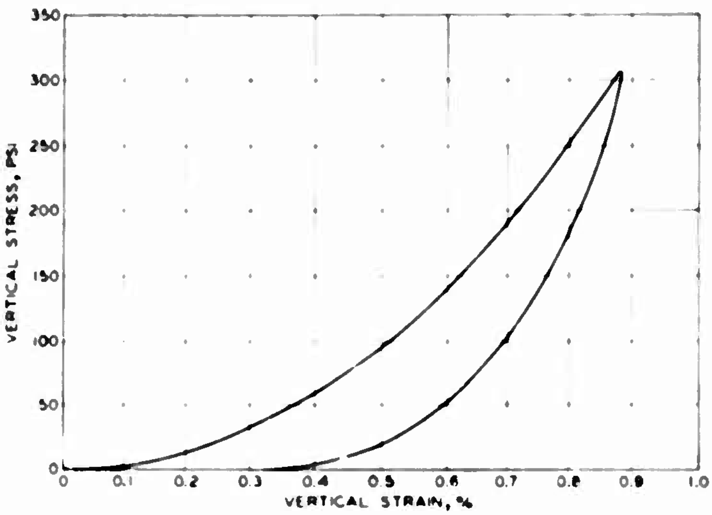
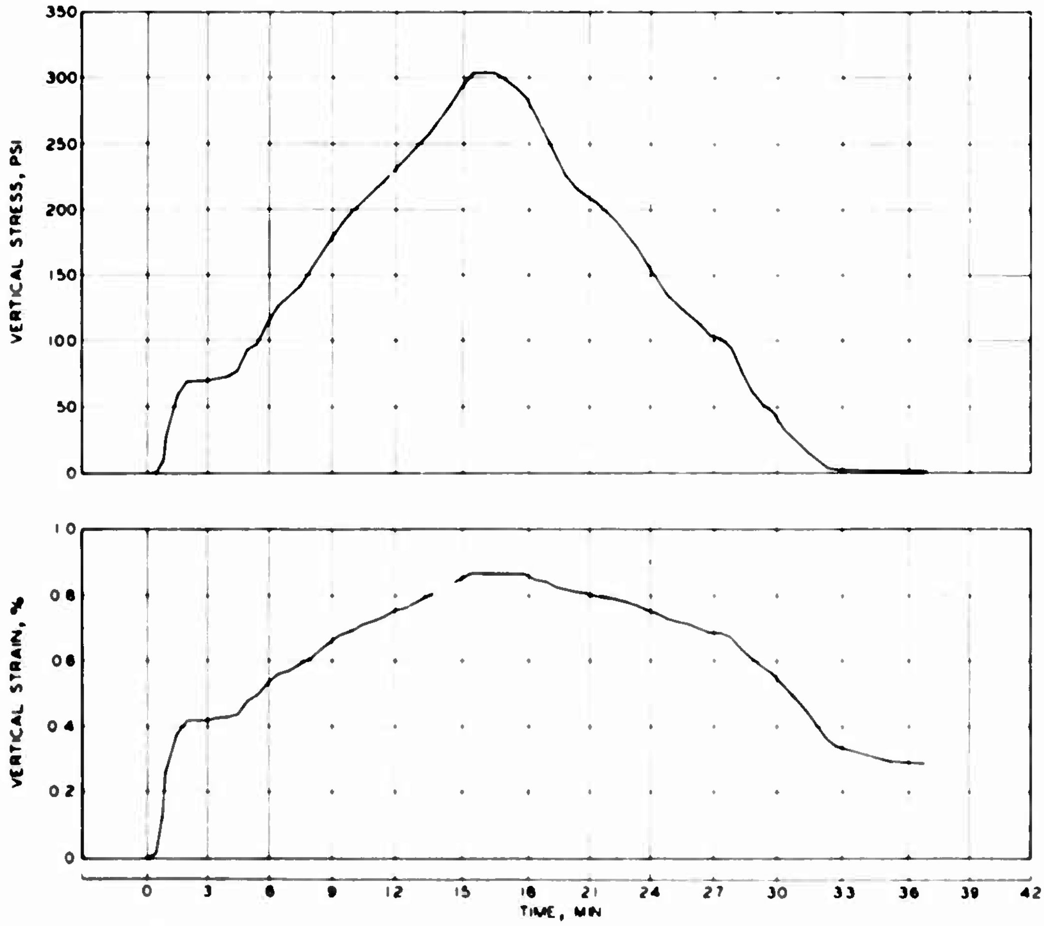


Fig. 119. Results of Test No. A01A01 in preliminary testing program.



TEST INFORMATION

TEST NO A01A02
I D NO 112098
SOIL TYPE REID-BEDFORD MODEL SAND
RELATIVE DENSITY 93.7 PERCENT
SATURATION 0.0 PERCENT
SPECIMEN THICKNESS 2.5 INCHES
CONFIGURATION AUXILIARY

NOTE BASIC LONG-DURATION TEST
WITH 2½-IN SOIL SPECIMEN

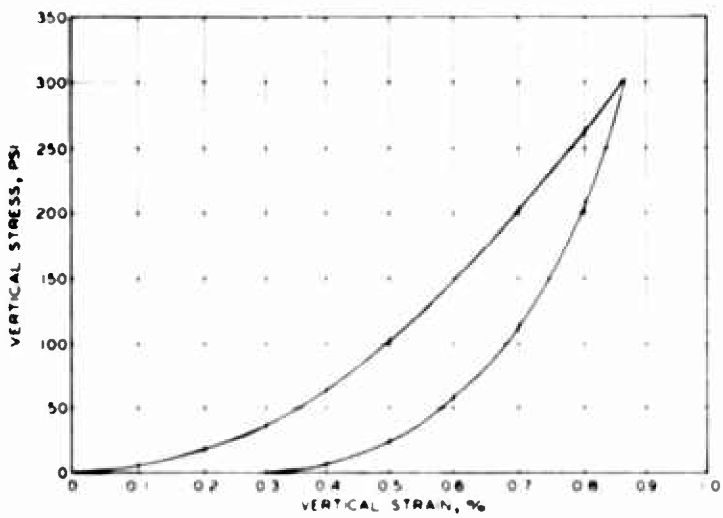
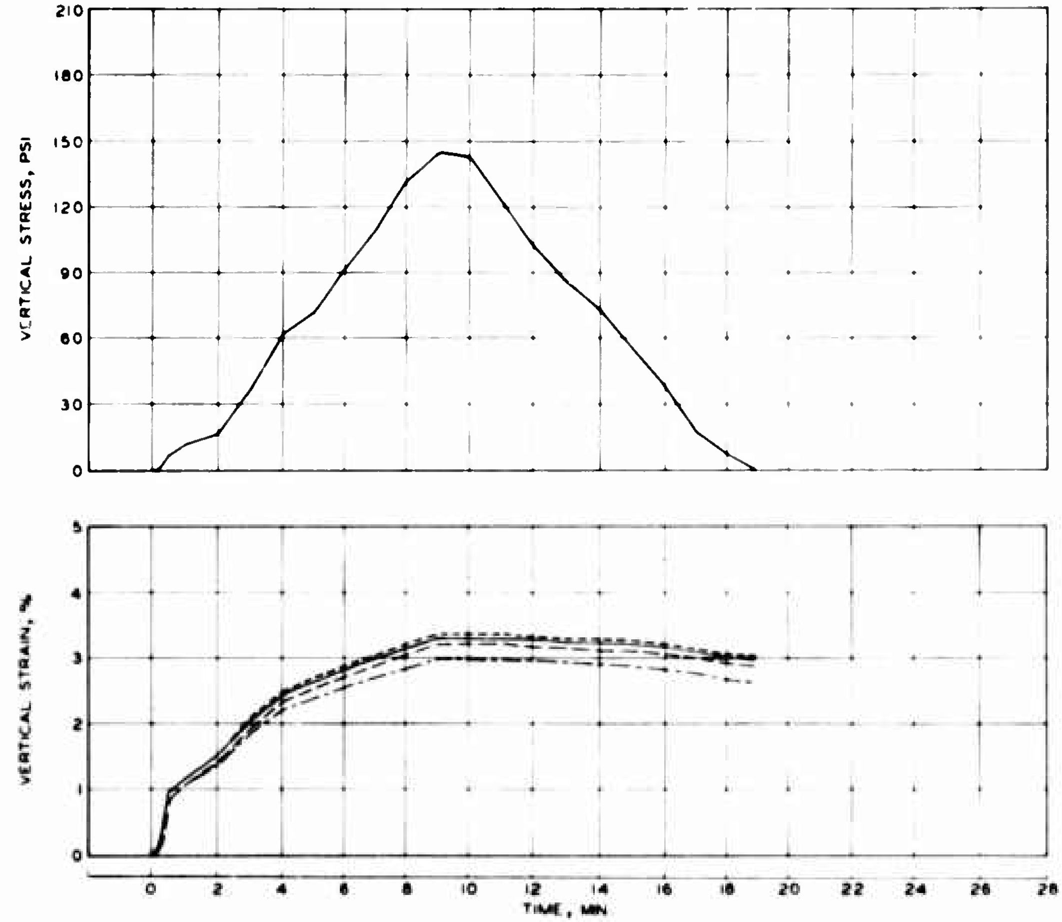


Fig. 120. Results of Test No. A01A02 in preliminary testing program.



TEST INFORMATION

TEST NO A01A03
I D NO 112286
SOIL TYPE REID-BEDFORD MODEL SAND
RELATIVE DENSITY -2 3 PERCENT
SATURATION 0 0 PERCENT
SPECIMEN THICKNESS 2 5 INCHES
CONFIGURATION AUXILIARY

NOTE TEST FOR INDICATION OF SIDEWALL-FRICTION EFFECT

LEGEND

———	LVDT 0
·······	LVDT 2
— — —	LVDT 3
—·—	LVDT 4

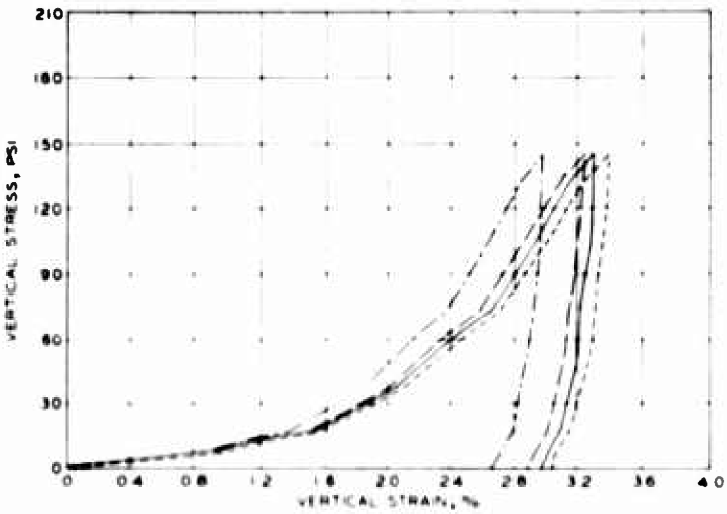


Fig. 121. Results of Test No. A01A03 in preliminary testing program.

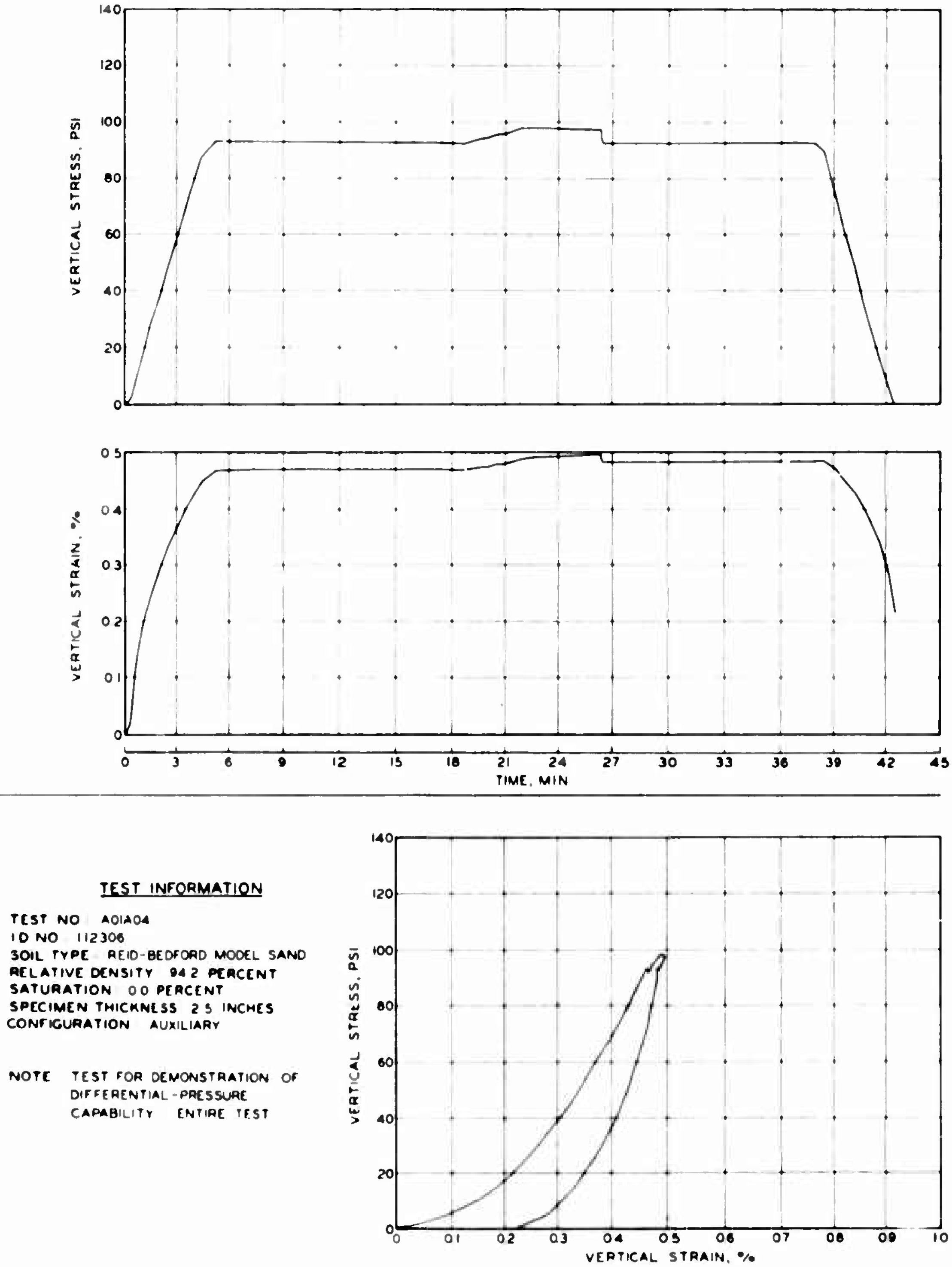


Fig. 122. Results of Test No. A01A04 in preliminary testing program; entire test.

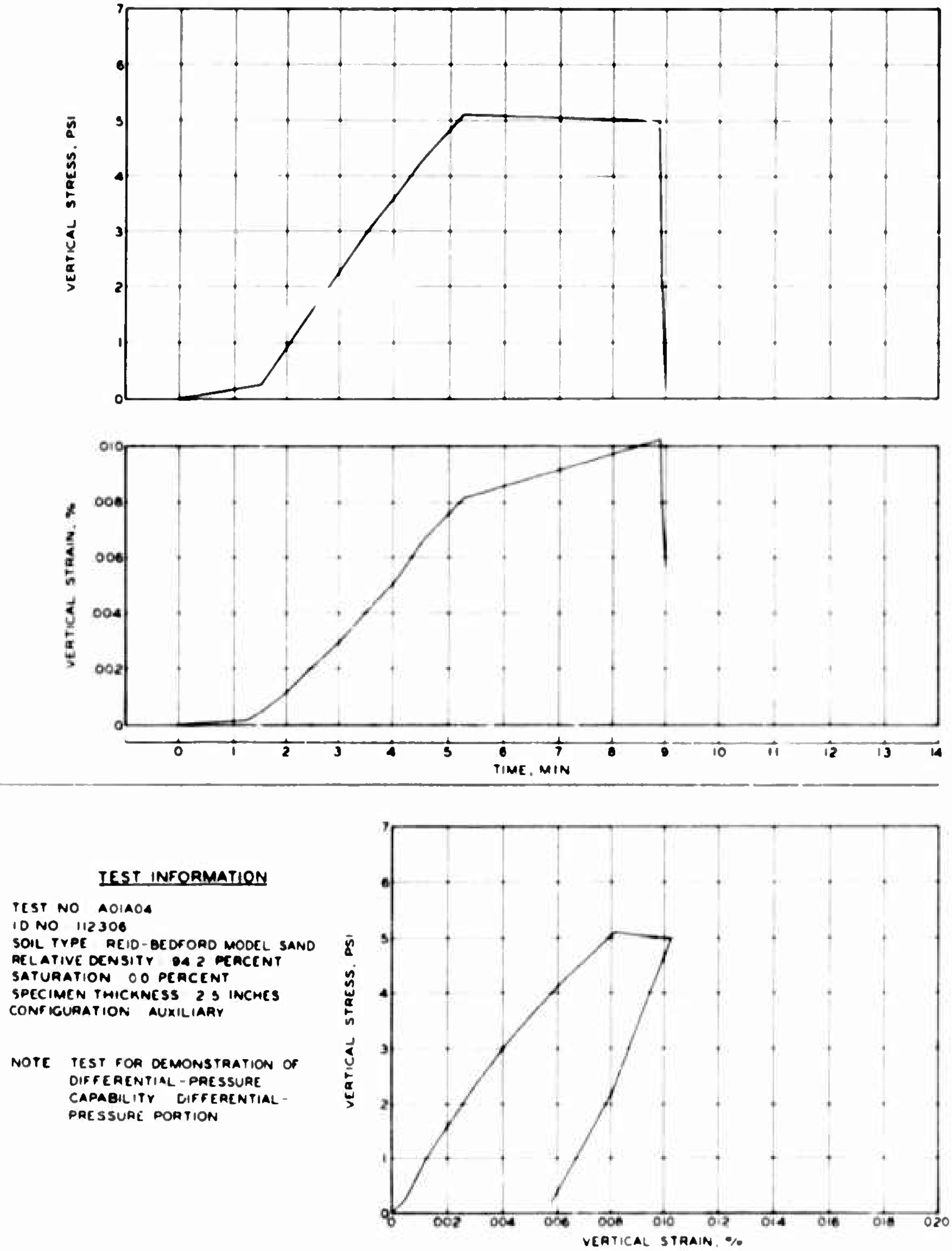
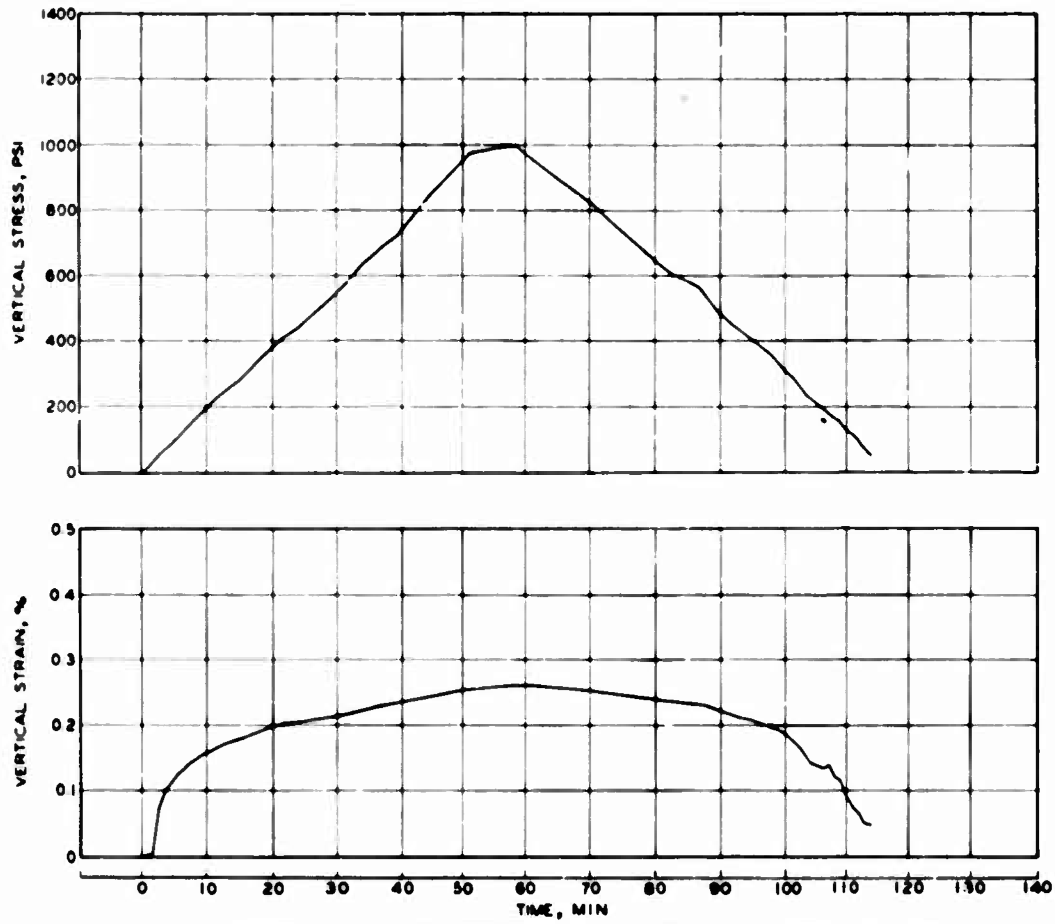


Fig. 123. Results of Test No. A01A04 in preliminary testing program; differential-pressure portion.



TEST INFORMATION

TEST NO A01A05
I D NO 101047
SOIL TYPE STEEL PLATE
RELATIVE DENSITY NA
SATURATION NA
SPECIMEN THICKNESS 1.0 INCH
CONFIGURATION AUXILIARY

NOTE SIMULATION OF RIGID SPECIMEN (EITHER PREPARED OUTSIDE THE SOIL CHAMBER OR SAMPLED FROM LARGER MASS)

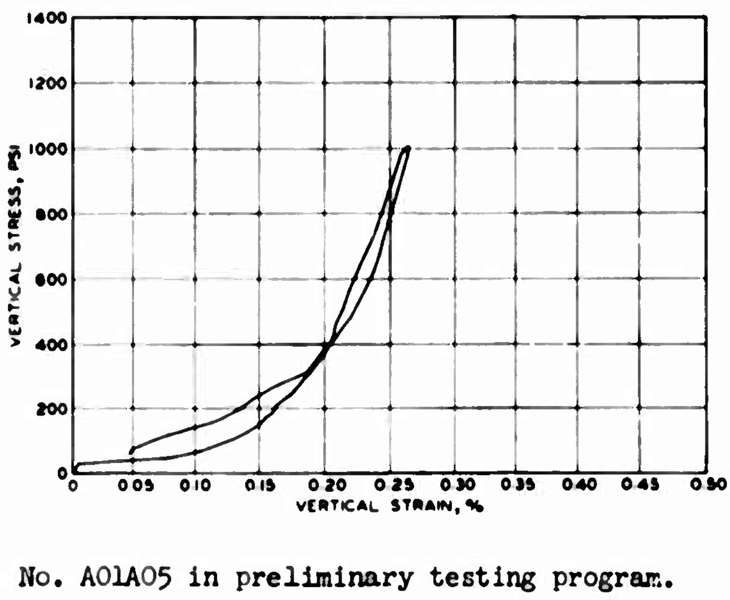
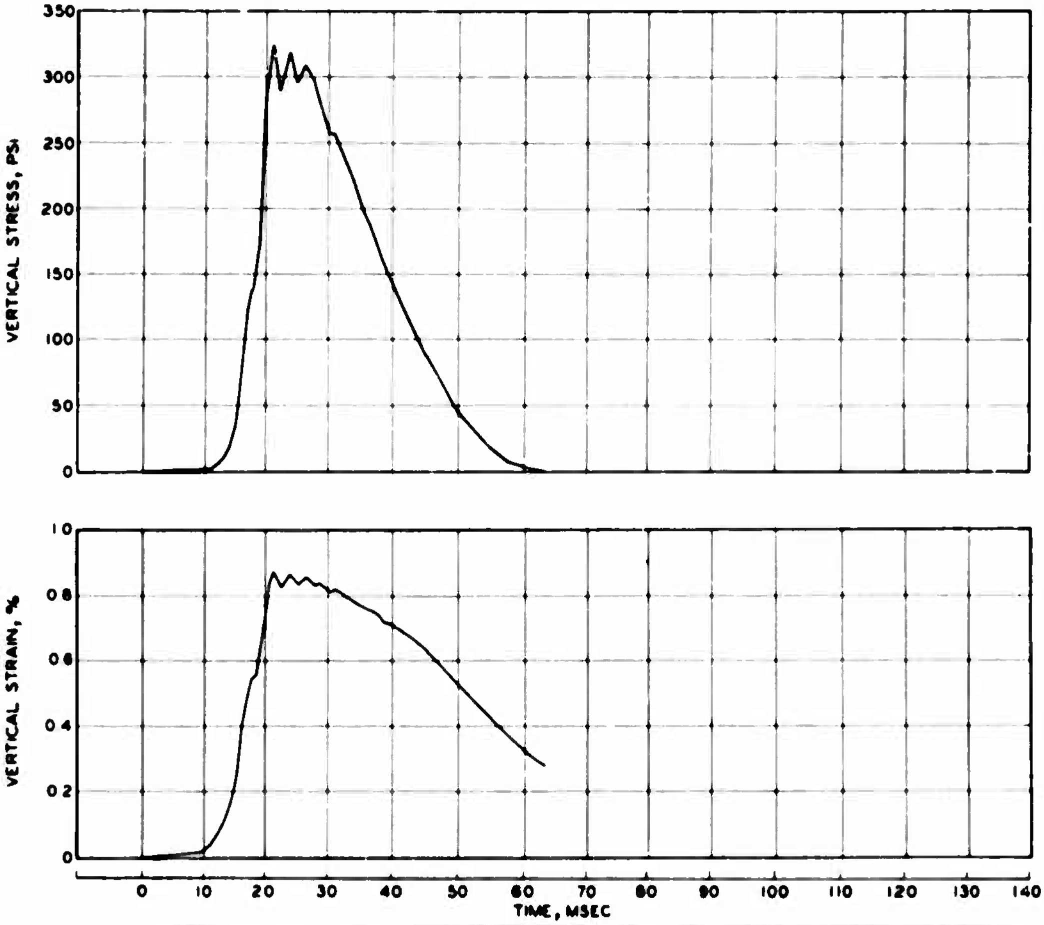


Fig. 124. Results of Test No. A01A05 in preliminary testing program.



TEST INFORMATION

TEST NO: A01P01
ID NO. 201137
SOIL TYPE: REID-BEDFORD MODEL SAND
RELATIVE DENSITY: 93.2 PERCENT
SATURATION: 0.0 PERCENT
SPECIMEN THICKNESS: 1.0 INCH
CONFIGURATION: PRINCIPAL

NOTE: MINIMUM DECAY VALVE SETTING 1-IN. SOIL SPECIMEN

MEMBRANE CAME OFF FLUID CONTAINER DURING DISASSEMBLY, PERMITTING SOME WATER (PRESSURE FLUID) TO ENTER SPECIMEN. RELATIVE DENSITY AND SATURATION VALUES ABOVE ARE ASSUMED VALUES

SMALL DWELL TIME INADVERTENTLY OBTAINED

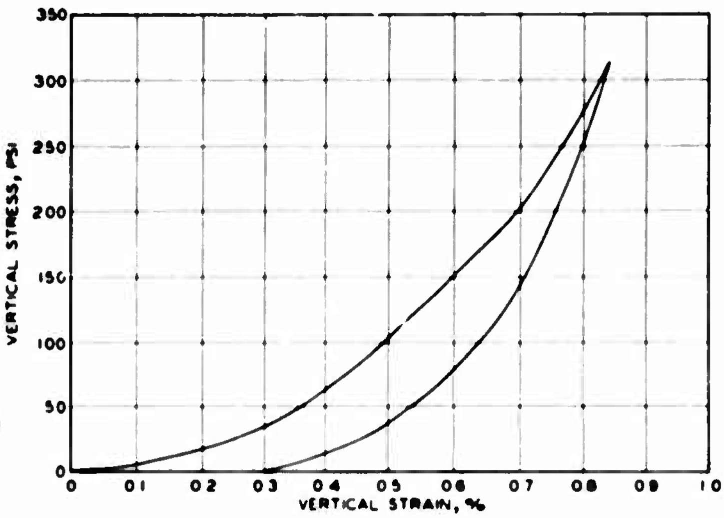


Fig. 125. Results of Test No. A01P01 in preliminary testing program.

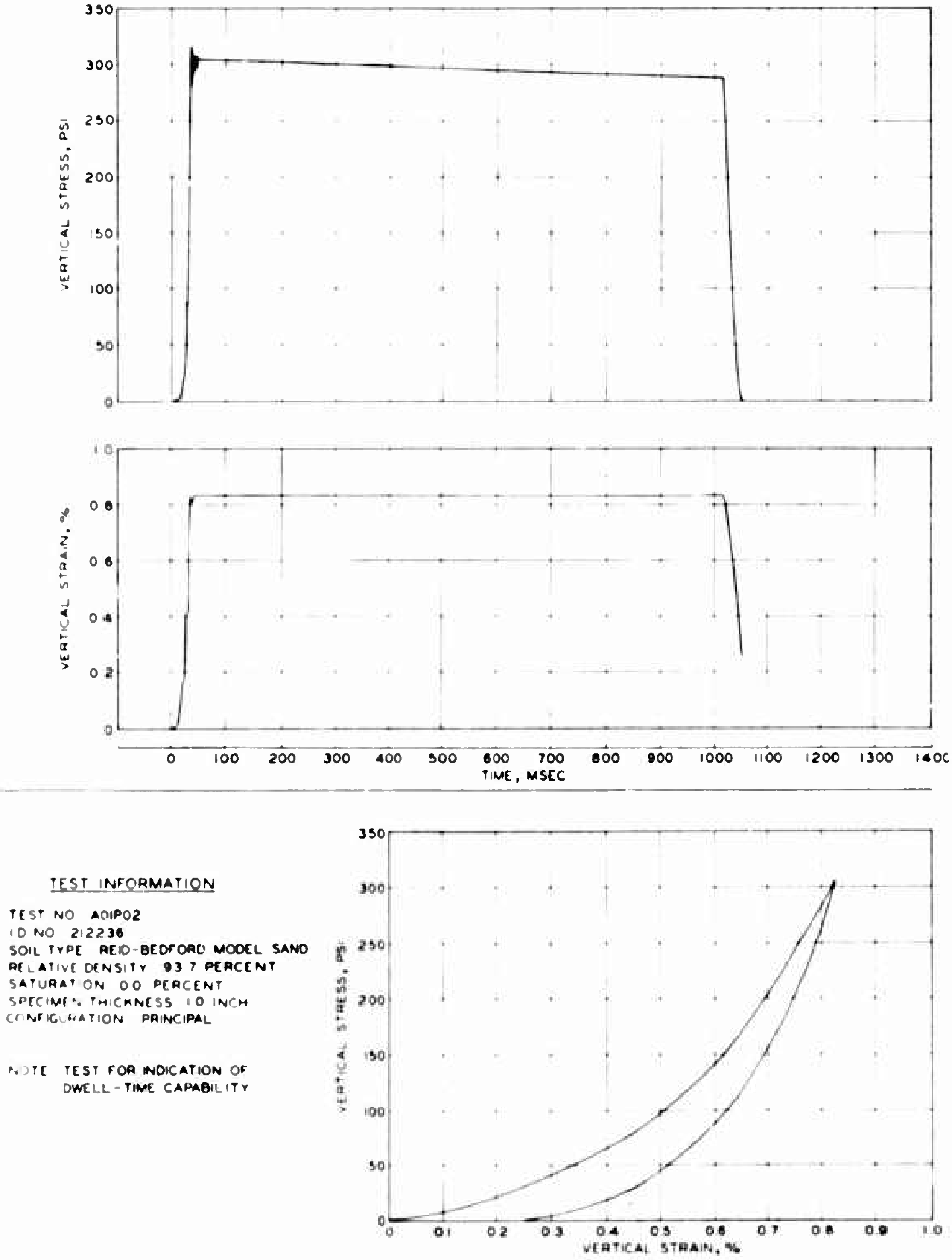
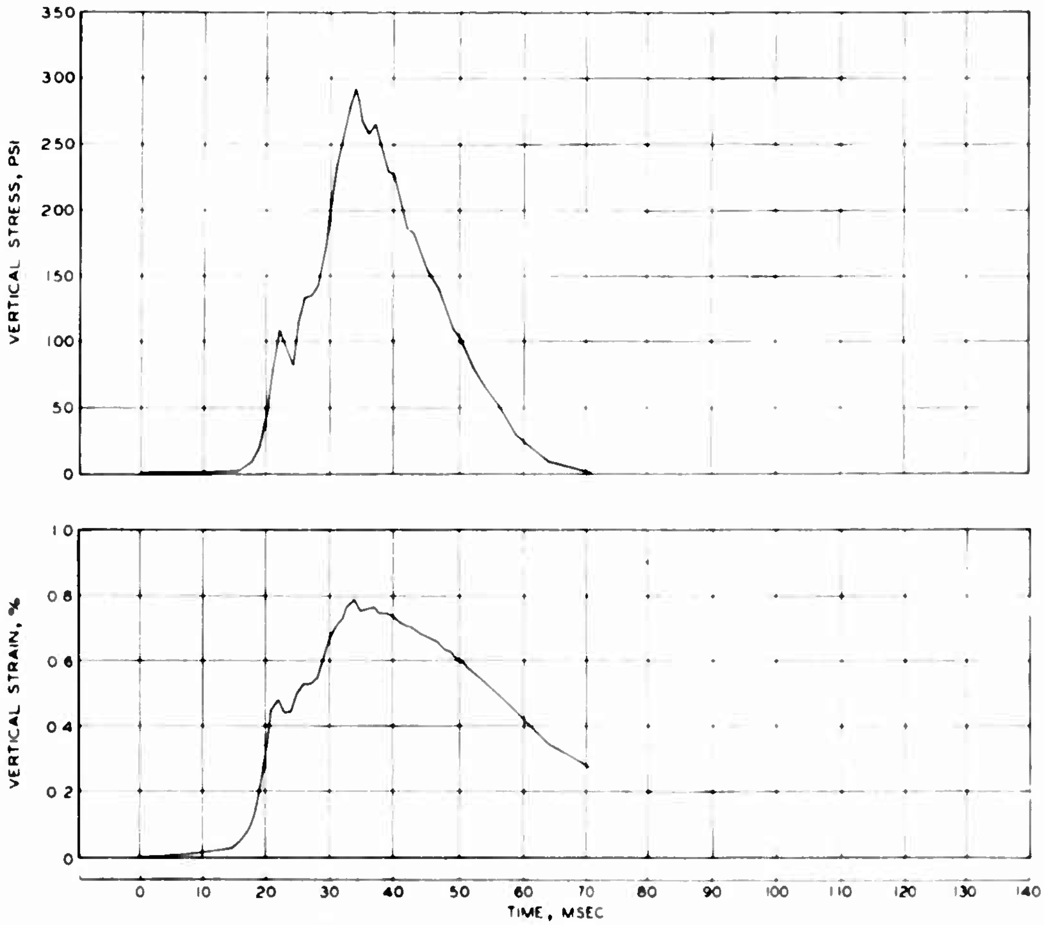


Fig. 126. Results of Test No. A01P02 in preliminary testing program.



TEST INFORMATION

TEST NO A01P03
I D NO 212156
SOIL TYPE REID-BEDFORD MODEL SAND
RELATIVE DENSITY 94 2 PERCENT
SATURATION 0 0 PERCENT
SPECIMEN THICKNESS 2 5 INCHES
CONFIGURATION PRINCIPAL

NOTE MINIMUM DECAY VALVE SETTING, $2\frac{1}{2}$-IN SOIL SPECIMEN

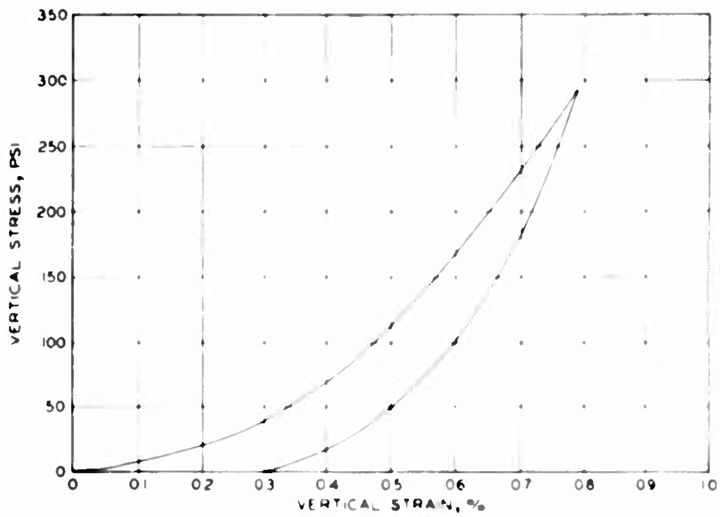
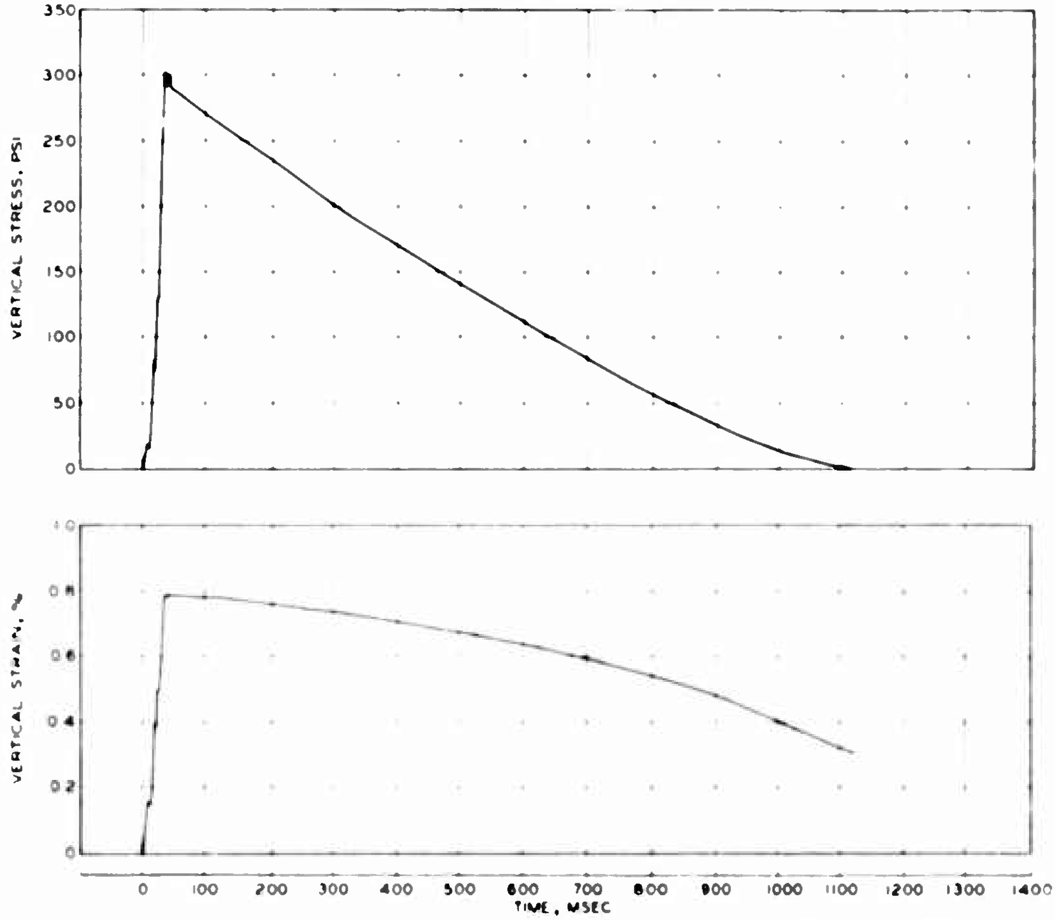
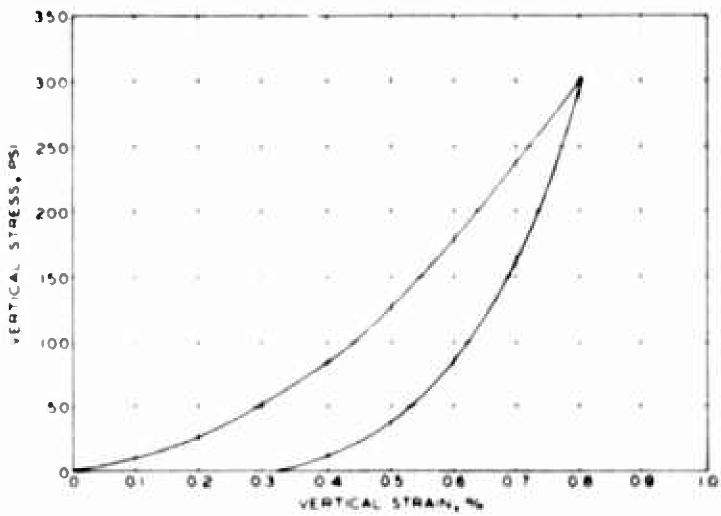


Fig. 127. Results of Test No. A01P03 in preliminary testing program.



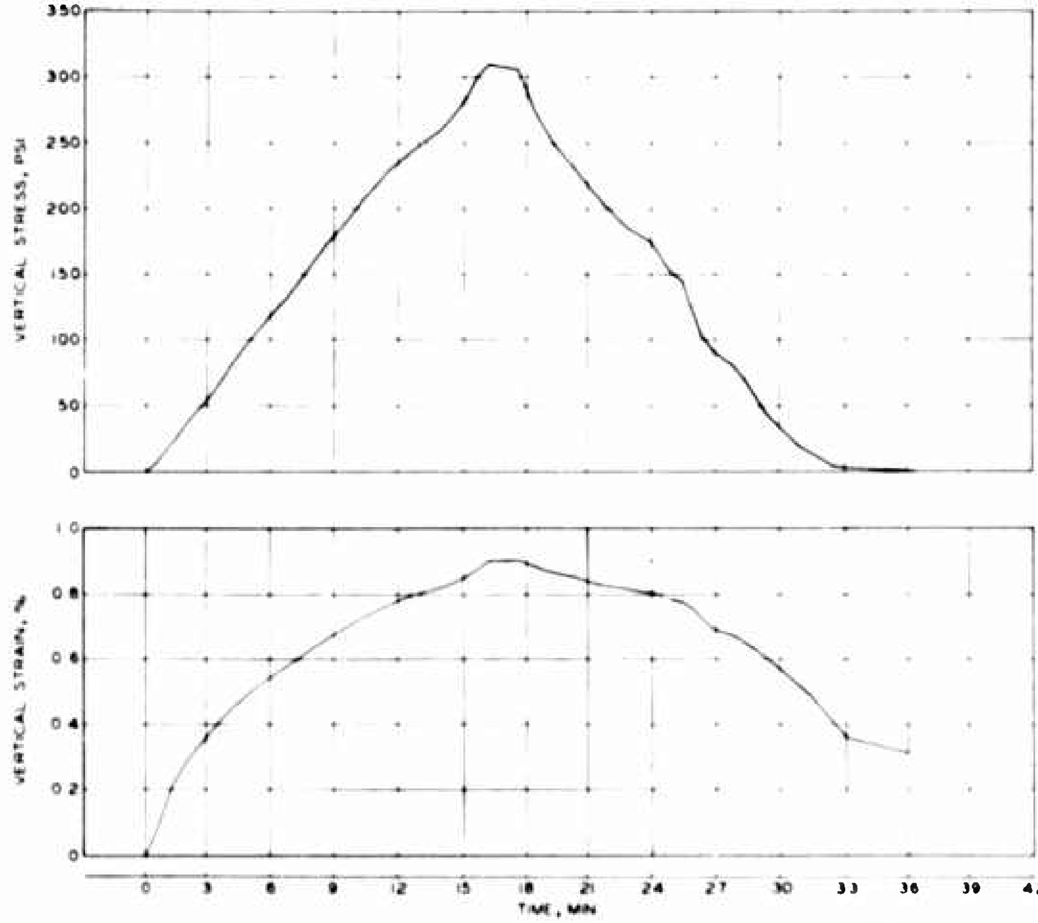


TEST INFORMATION

TEST NO A01P04
I.D. NO 212196
SOIL TYPE REID-BEDFORD MODEL SAND
RELATIVE DENSITY 93.2 PERCENT
SATURATION 0.0 PERCENT
SPECIMEN THICKNESS 2.5 INCHES
CONFIGURATION PRINCIPAL

NOTE SIMULATION (BY IMPULSE) OF SURFACE OVERPRESSURE FROM 100-MT NUCLEAR SURFACE BURST

Fig. 128. Results of Test No. A01P04 in preliminary testing program.



TEST INFORMATION

TEST NO. A01R01
I.D. NO. 112226
SOIL TYPE: REID-BEDFORD MODEL SAND
RELATIVE DENSITY: 82.6 PERCENT
SATURATION: 0.0 PERCENT
SPECIMEN THICKNESS: 1.0 INCH
CONFIGURATION: AUXILIARY

NOTE: REPEAT OF TEST NO. A01A01

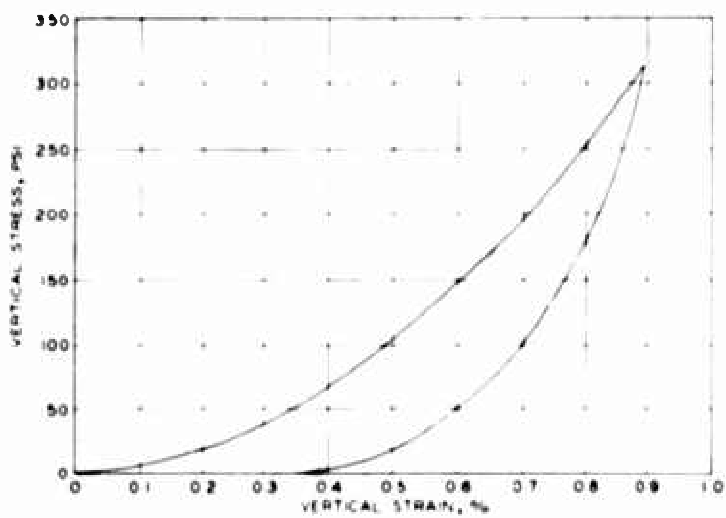


Fig. 129. Results of Test No. A01R01 in preliminary testing program.

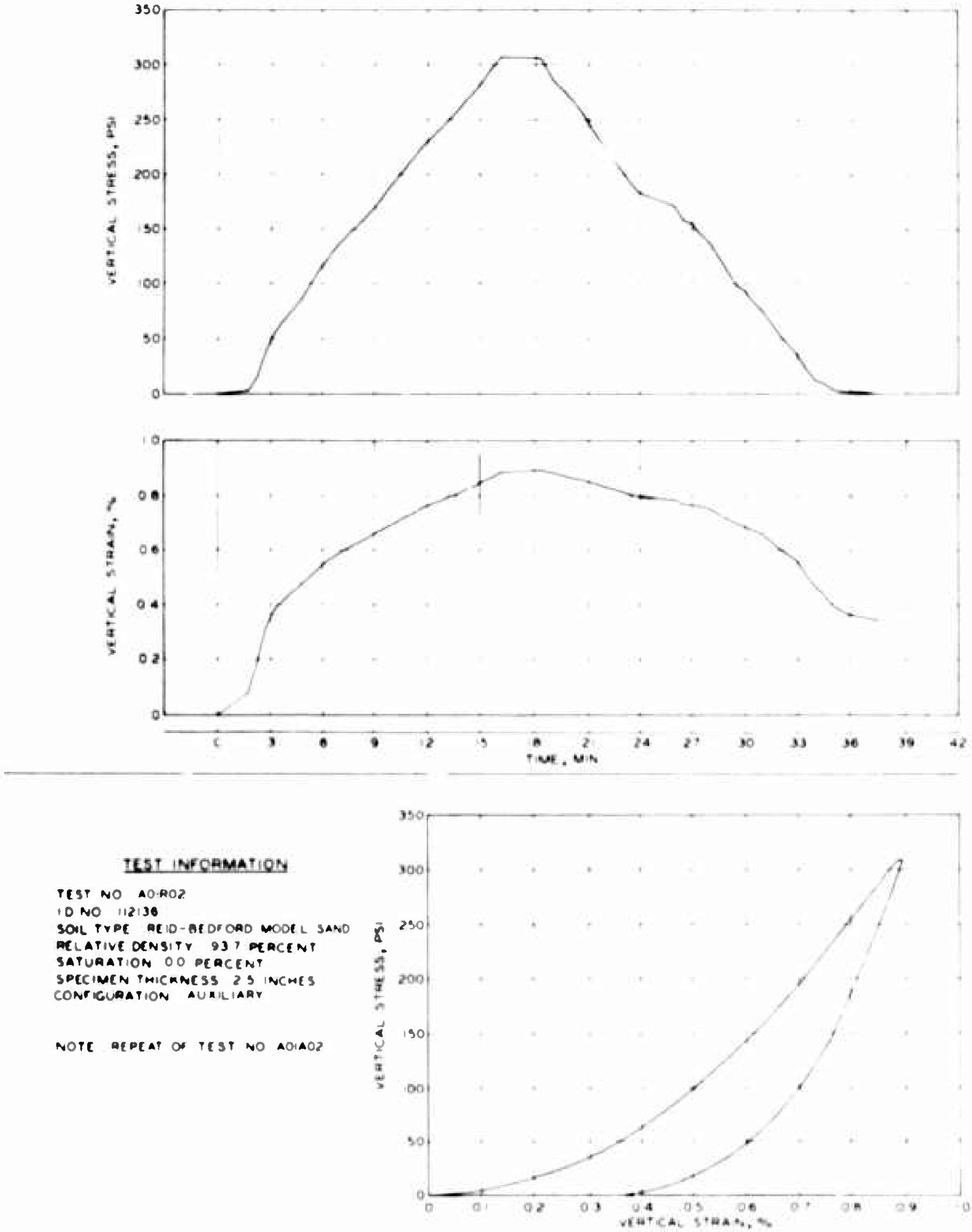
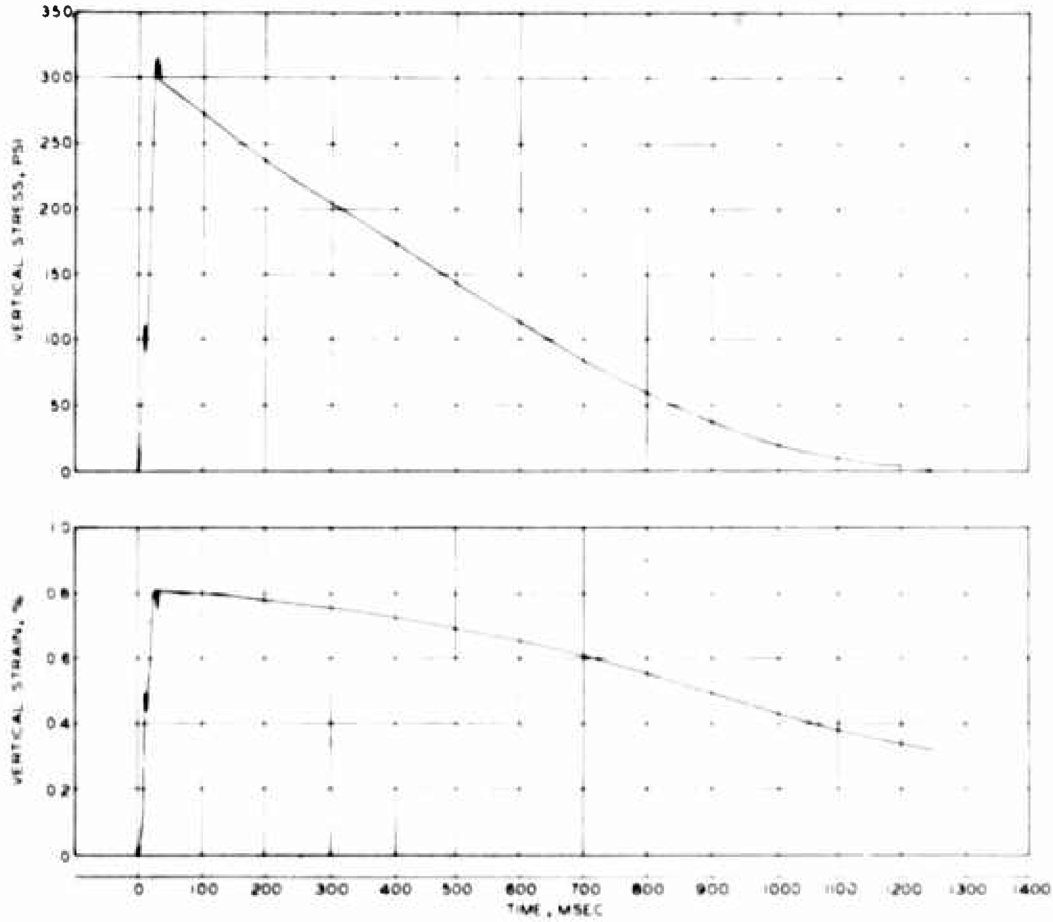


Fig. 130. Results of Test No. A01R02 in preliminary testing program.



TEST INFORMATION

TEST NO A01R03
I D NO 201237
SOIL TYPE REID-BEDFORD MODEL SAND
RELATIVE DENSITY 94 2 PERCENT
SATURATION 0 0 PERCENT
SPECIMEN THICKNESS 2 5 INCHES
CONFIGURATION PRINCIPAL

NOTE REPEAT OF TEST NO A01P04

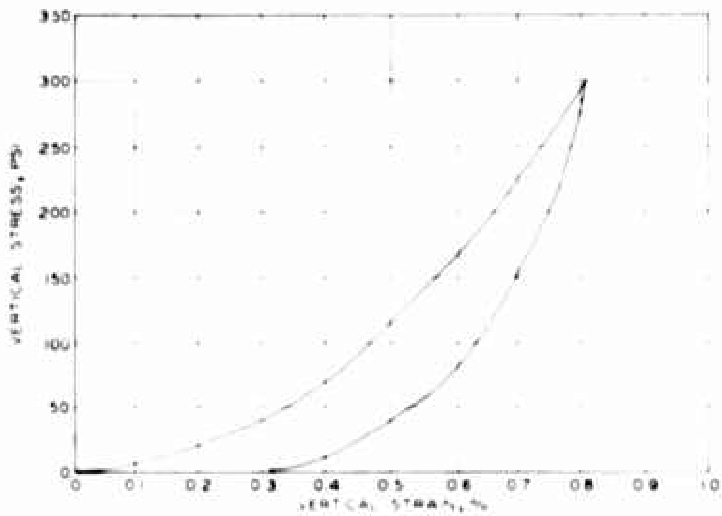


Fig. 131. Results of Test No. A01R03 in preliminary testing program.

VITA

Larry Schindler [redacted]. He attended secondary schools in Brooklyn, New York, and was graduated in June 1953. After several years as an Evening-Session student at Cooper Union and at the College of the City of New York, he transferred to the regular Day Session at City College in June 1958. He was graduated from City College in June 1960, Magna Cum Laude and first in his class, with a Bachelor of Civil Engineering degree. Upon graduation, he was awarded a three-year, National-Defense-Education-Act Title IV Fellowship through the University of Illinois. He enrolled in the Graduate College of the University of Illinois in September 1960, received a Master of Science degree in Civil Engineering in June 1961, and remained on campus until September 1963, when he left to complete the work for his thesis at the U. S. Army Engineer Waterways Experiment Station in Vicksburg, Mississippi.

While attending the Evening Session at Cooper Union and at City College, he was employed as an Estimator and Inspector by the consulting engineering firm of Andrews and Clark. He returned to Andrews and Clark as an Estimator during the summer of 1960. During the summer of 1961, he was employed as a Research Civil Engineer by E. H. Plesset Associates, Inc., and during the summer of 1962, he was employed as a Soils Engineer by Fruco and Associates, Inc. While at the University of Illinois, he taught courses in soil mechanics theory and principles and in engineering and construction economy. From September 1963 to September 1967, he was employed as a Senior Project Engineer by the U. S. Army Engineer Waterways Experiment Station, where he planned, supervised, and reported (to sponsoring

agency) all research, in-house and contract, dealing with free-field aspects of overall nuclear-weapons-effects research program, and where he conducted research on constrained-modulus characteristics of soils, evaluated research proposals, and designed and supervised construction of equipment for the Soil Dynamics Test Facility. In September 1967, he joined the staff of the Chief of Engineers, Department of the Army, as a General Engineer in the Missiles and Protective Structures Branch of the Military Construction Directorate, where he plans, directs, and coordinates protective-structures research required by the Corps of Engineers to fulfill its mission, develops engineering criteria for specific protective-structures installations, and serves as advisor and consultant in the fields of soil and rock dynamics.

He is a registered Professional Engineer in the State of Mississippi and a member of Sigma Xi, Chi Epsilon, American Society of Civil Engineers, and American Society of Engineering Education.

He is the author of a paper, entitled "An Improved Facility for Testing Soils in One-Dimensional Compression," which is included in the Proceedings of the Symposium on Wave Propagation and Dynamic Properties of Earth Materials. In June 1967, he received an official commendation and cash award from the Department of the Army in recognition of his efforts in designing and evaluating a unique device for determining the properties of soils under short-duration loadings.

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DD FORM 1 NOV 65 **1473** REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Impulse loads						
Soil dynamics						
Soil properties						
Nuclear explosion effects						
Test facilities						

Unclassified

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